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STUDY S-104

PROCEEDINGS OF THE IDA PULSE-POWER CONFERENCE

February 4-5, 1963

VOLUME I:
UNCLASSIFIED PAPERS ON INDUCTIVE ENERGY STORAGE, MAGNETOHYDRODYNAMICS EXPLOSIVE-TRANSDUCERS, AND SWITCHING

INSTITUTE FOR DEFENSE ANALYSES
RESEARCH AND ENGINEERING SUPPORT DIVISION

March, 1963

IDA/HQ 63-1412

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Contract SD-50

CONTENTS

		Page
I	INTRODUCTION (R.C. Hamilton, IDA)	1
II	INDUCTIVE ENERGY STORAGE	
	Principles of Inductive Energy Storage (H.C. Early, University of Michigan)	2
	10^8-Joule Inductive Energy Storage System (M.D. Horton, General Electric Company)	19
	Capacitance and Inductance Energy Storage Systems at AEDC (R.R. Walker, III, von Kármán Gas Dynamics Facility, ARO, Inc.)	28
	Inductive Energy Storage for High-Energy Pulses (L.A. Kilgore, P. Hawkshaw, & C.H. Church. Westinghouse Electric Corp.)	35
	Summary (R.C. Hamilton, IDA)	39
	General References	40
III	SUPERCONDUCTING INDUCTIVE ENERGY STORAGE	
	Energy Storage in Superconducting Coils for High Pulsed Power Applications (W.F. Hassel, Jet Propulsion Center, Purdue University)	41
	Magnetic Energy Storage Using Superconducting Coils (Z.J.J. Stekly, Avco-Everett Research Laboratory	53
	Note on Superconductive Inductor Energy Storage (with two Appendixes) (K.H. Fischbeck and J.J. Hanak, RCA Laboratory, Princeton N.J.)	76
	Energy Storage in Superconducting Solenoids (J.K. Huhn, Westinghouse Electric Corp.)	106
	A Cryogenic System to Refrigerate a Superconducting Inductor (J.A. Carlson, R.A. Flinn, and G. Siegrist, Air Products & Chemicals Co.)	110
	Summary (R.C. Hamilton, IDA)	123
	General References	124

CONTENTS (Cont)

		Page
IV	MAGNETOHYDRODYNAMICS	
	High-Power, Short-Duration MHD Power Plants (Stuart Hamilton, Pratt & Whitney Aircraft)	125
	Very High Power, Limited Duty Cycle Rocket-Driven MHD Generators (A. Kantrowitz and Thomas Brogan, Avco-Everett Research Laboratory)	132
	Summary (R. C. Hamilton, IDA)	163
	General References	164
V	EXPLOSIVE TRANSDUCERS	
	Explosive (XMHD) Generators for Ultra High Power Pulses (A. T. Biehl, MB Associates)	165
	Generation of Electric Power from Explosives (V. H. Blackman, M. S. Jones, and C. N. McKinnon, MHD Research, Inc.)	171
	Summary (R. C. Hamilton, IDA)	174
	General References	175
VI	SWITCHING AND CONTROL	
	Present Technology of Large Switchgear (C. H. Titus, General Electric Company)	176
	Switching Inductive Energy Storage Apparatus (H. C. Early, University of Michigan)	180
	Summary (R. C. Hamilton, IDA)	194
	General References	195
VII	GENERAL SUMMARY (R. C. Hamilton, IDA)	196

I INTRODUCTION

INTRODUCTION

Robert C. Hamilton

Institute for Defense Analyses

The energy storage capacity at the Arnold Engineering Development Center, Tullahoma, Tennessee, for hypersonic wind tunnel testing has increased in recent years from 10^5 to 10^8 joules. A technical conference was held on February 4 and 5, 1963, at the Institute for Defense Analyses to review the technology of pulse power generation and energy storage. The unclassified non-proprietary papers on inductive energy storage, superconducting coils, magnetohydrodynamics, explosive transducers, and switching are presented in this volume.

II INDUCTIVE ENERGY STORAGE

PRINCIPLES OF INDUCTIVE ENERGY STORAGE

H. C. Early

University of Michigan

Storage of energy in a magnetic field, as illustrated in Fig. 1, is best adapted to applications where the energy is to be extracted during a time interval of a few milliseconds (Ref. 1). For longer discharge intervals, rotating machinery may be more economical, while for discharge intervals of the order of one millisecond or less, the switching problem of opening a very-high-current circuit with sufficient speed becomes difficult. If a new technique for fast circuit interruption could be devised, representing a major breakthrough from present methods, then, inductively stored energy might also be economically feasible for generating high-power pulses in the microsecond range.

The economics of inductive storage are intimately related to the type of d-c power source and the pulse repetition rate required. With some types of d-c power supplies, such as rotating machinery or MHD, the important factor in the cost may be the <u>peak power</u> required near the end of the charging interval, and the total energy expended in charging the coil is less significant. For other supplies, such as batteries, the peak-power requirement may be less important than the <u>efficiency</u> of the process, i.e., the fraction of the total energy expended that is stored and available from the inductor. An optimum design will always be a compromise between the two objectives of minimum peak power and maximum efficiency. The two cases will be discussed separately.

Storage Where the Peak Charging Power Requirement is the Major Cost Factor

The following discussion is based on several simplifying assumptions:

1. The cost of the d-c power supply is proportional to the peak capacity in kilowatts. (This assumption holds roughly over a considerable range, but at large power levels, the cost per kilowatt tends to become less.)
2. The current density in the conductor is kept low enough so that the compressive magnetic forces do not become excessive (as will be discussed later).
3. The coil conductors have enough thermal capacity so that cooling is not an important economic factor.
4. The cost of the coil is proportional to its volume, i.e., proportional to the cube of a linear dimension.
5. The charging time is long enough so that the current is nearing the steady-state value.

In evaluating various coil designs, a figure of merit may be defined which relates the total energy stored at peak current to the peak charging power.

$$\text{Figure of merit} = \frac{\text{stored energy}}{\text{peak charging power}} = \frac{(1/2)\, LI_m^{\,2}}{I_m^{\,2}R} = 1/2\,\frac{L}{R} = 1/2\,(\text{coil time constant})$$

where

L = inductance of the coil, henrys

R = resistance of the coil, ohms

I_m = peak coil current, amperes

This definition of a figure of merit is helpful in comparing the relative advantages of different coil sizes and shapes. Consider a multiple-layer coil, having a mean radius a. For a given coil shape, the inductance is proportional to the square of the number of turns and to the first power of a given coil dimension, $L = (\text{constant})\ an.^2$ The resistance is also proportional to the square of the number of turns, but is inversely proportional to the first power of a given coil dimension, $R = (\text{constant})\ n^2/a$.

Therefore, for any given shape, the following obtains:

$$\text{figure of merit} = 1/2\,\frac{L}{R} = 1/2\,\frac{(\text{constant})an^2}{(\text{constant})n^2/a} = (\text{constant})a^2$$

and the relation of stored energy to peak charging power varies as the square of the given coil dimension. Thus, for a given volume or weight of conductor, the figure of merit is immediately specified regardless of whether the coil is wound of many turns of small wire or a few turns of large wire. (This statement neglects the effect on L and R of insulation spacing.) From the foregoing relationship, it can be seen that increasing the linear dimensions of a coil by a factor k will increase the ratio of stored energy to peak power by a k^2 factor.

On the basis of the assumptions stated previously, several important relations can be derived.

Let

$\$_p$ = cost of power supply

$\$_c$ = cost of coil

Then

$$\text{figure of merit} = \frac{\text{joules}}{\text{watt}} = (\text{constant})\,(\text{coil volume})^{2/3} = (\text{constant})\,(\$_c)^{2/3}$$

$$\text{storage capacity} = \frac{\text{joules}}{\text{watt}}\,(\text{peak power}) = (\text{constant})\,(\$_c)^{2/3}(\$_p)$$

$$\text{joules/dollar} = \frac{\text{storage capacity}}{\text{total cost}} = (\text{constant})\,\frac{(\$_c)^{2/3}(\$_p)}{(\$_c + \$_p)}$$

For a given total cost ($\$_c + \$_p$), maximum stored energy is obtained for an optimum ratio $\$_p/\$_c$. The optimum ratio is 3/2. However, the ratio $\$_p/\$_c$ can vary from unity to 5/2 without decreasing the joules/dollar more than 4%.

By substituting $\$_p/\$_c = 3/2$ in the foregoing relations, the following results are obtained:

total cost $= \$_c + \$_p = 5/2\ \$_c = 5/3\ \$_p$

storage capacity $=$ constant $(\$_c)^{5/3}$ $=$ constant (total cost)$^{5/3}$

joules/dollar $=$ constant (total cost)$^{5/3}$

joules/dollar $=$ constant (storage capacity)$^{2/5}$

Fig. 2 illustrates the trend of joules/dollar of capacitive and inductive storage, as storage capacity is increased. For the small installation, capacitors are less expensive, but the inductance becomes progressively more advantageous as the size of the system increases.

Fig. 3 illustrates power relationships for a coil charging from a constant supply voltage. The horizontal coordinate is the charging time measured in units of the coil time constant, $\nu = \frac{L}{R}$. The vertical coordinate gives the instantaneous power drawn from the d-c supply, as well as the instantaneous power being delivered to the magnetic field. After about two time constants, most of the power is lost as resistive heating as the current nears its steady-state value. If the d-c power source has a drooping voltage as the current rises, than the relationships shown in Fig. 3 will be of limited applicability.

In some applications, for generating repetitive pulses, the peak charging power available could be used more effectively if several inductive storage coils were charged from the same d-c charging source. The charging intervals for the various storage coils could overlap and could be staggered so as to represent a more uniform load on the power supply. Such a system might also be designed to have a greater reliability in case of failure of an interrupting switch.

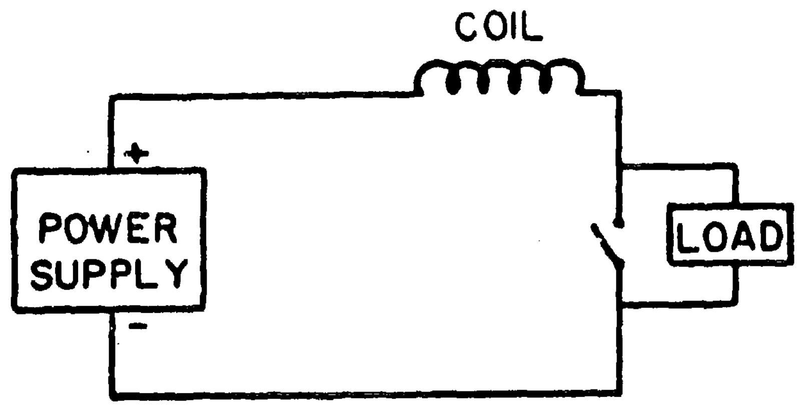

Fig. 1. Basic circuit for inductive energy storage

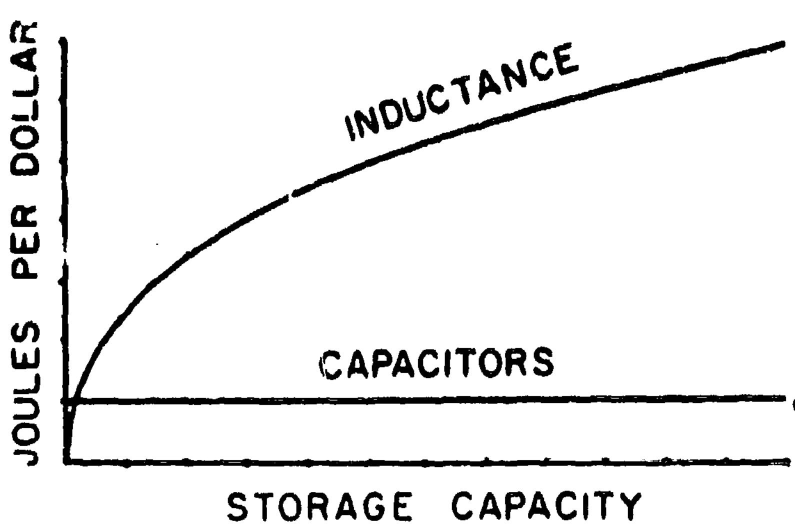

Fig. 2. Trend of joules per dollar vs. energy storage capacity

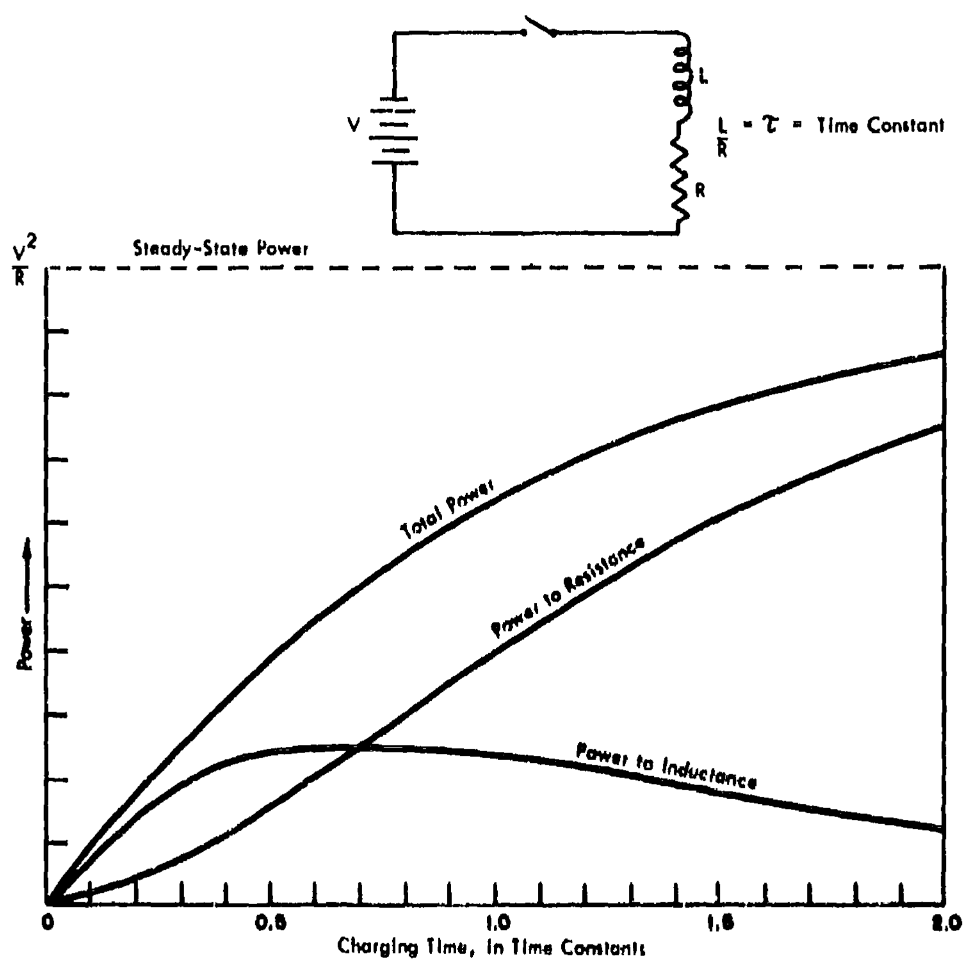

Fig. 3. Instantaneous power transfer vs. time

Storage Where Efficiency of Energy Transfer is a Major Cost Factor

Fig. 4 illustrates the efficiency of the storage process as a function of the charging time measured in units of the coil time constant. A constant d-c supply voltage is assumed. The vertical coordinate is the ratio of energy stored to the total energy consumed. For a charging time of 0.1 time constant, the storage system is 93% efficient, while with a charging time of 1.0 time constant, the efficiency drops to 54%.

Coil Heating

For repetitive operations, a choice can be made between using (1) a large coil (or several coils) which has enough thermal capacity to act as a heat sink for the required period of operation or (2) a cooling system such as a mechanism for releasing a liquified gas throughout the winding to absorb heat.

Fig. 5 illustrates temperature rise characteristics of aluminum coils during one charging operation from a constant voltage source. Three of the curves are for a charging time of one second, and two curves are for a charging time of 4 seconds.

The coil design used for computing the curves of Fig. 5 is the maximum inductance geometry (Ref. 2) where the axial length and radial depth of the winding are both equal to 0.66 times the mean radius. Such a coil having a 3-meter diameter has a time constant of 2.5 seconds, and the time constant scales with the square of the diameter.

Magnetic Pinch Forces on Coil Windings

The question arises as to whether or not scaled-up versions of existing energy-storage coils would encounter magnetic forces which would exceed the mechanical strength of commonly used conductors and insulating materials. The magnetic pinch

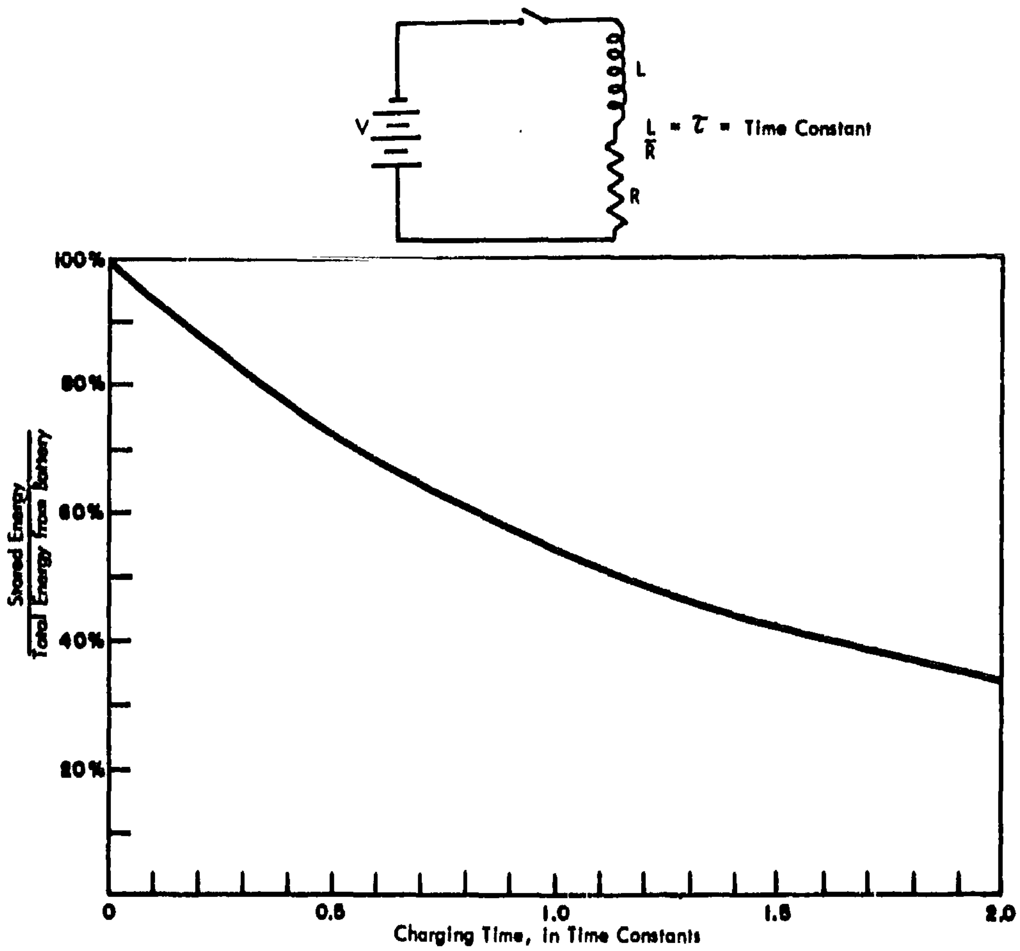

Fig. 4. Efficiency of energy transfer

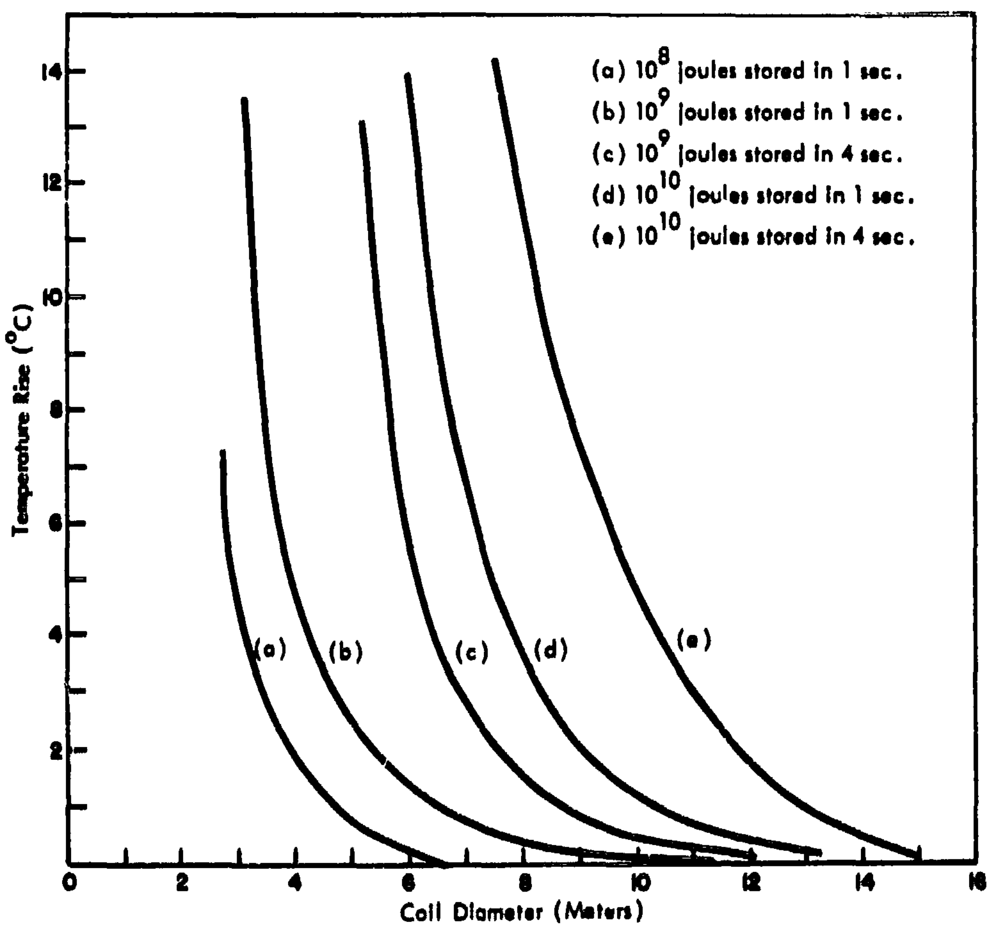

Fig. 5. Transient temperature rise vs. coil diameter

pressure at the center of a straight, round conductor is

$$\frac{\mu_0 I^2}{4\pi^2 R^2} \quad \text{newtons/m}^3 \qquad \text{Eq. (1)}$$

where R = radius in meters

I = current in amperes.

The total current equals $\pi R^2 J$, where J is the current density, and hence the pinch pressure is

$$\frac{\mu_0 R^2 J^2}{4} \quad \text{newtons/m}^3 \qquad \text{Eq. (2)}$$

This assumes that all the radial, inward, magnetic force developed throughout the cross section of the conductor is in hydrostatic equilibrium as in a conducting fluid.

This relation is still roughly correct if the straight conductor is bent into a circle and thus forms a toroidally shaped conducting ring having a minor radius R. The ring-shaped conductor can be replaced by a multilayer winding having the same cross-sectional area and average current density, and the maximum pinch pressure in the center of the winding of such a coil will be proportional to J^2R^2 as in Eq. (2).

If the coil were scaled up while maintaining a constant current density, J, the pinch pressure would increase as R^2, but if the current density in the scaled-up coil is decreased so that J varies as 1/R, then the magnetic pressure will not increase. It is easily shown that if the current density in the large coil is altered according to the above relation, the energy storage ($\frac{1}{2}$ L I^2) will be proportional to the cube of the radius.

An alternative justification of the above conclusion is as follows: The pressure exerted by a magnetic field on a boundary is proportional to B^2. The energy storage per unit volume is also proportional to B^2. Hence, in scaling up a coil, with

the pressure constant, the average energy density will also remain constant, and the total energy stored will be proportional to the volume or the cube of the radius.

There is also a magnetic force, tending to "stretch" the major diameter of the coil, and producing a tensile stress on the conductors. The maximum tensile stress can also be shown to remain constant if J varies as $\frac{1}{R}$.

The 10-joule, energy-storage coil at the Arnold Engineering Development Center has a diameter of 12 feet. If this coil were scaled up to 10^9 joules, according to the above relationships, the diameter would increase by a factor of $\sqrt[3]{10}$, or 2.15. For 10^{10} joules, the factor would be $\sqrt[3]{100}$, or 4.64, and for 10^{11} joules, the factor would be $\sqrt[3]{1000}$, or 10. The coil at AEDC was designed by the General Electric Company and has an excellent design for bringing out the terminal connections so as to minimize forces on the terminals. Larger coils would require on-site construction because of transportation problems, and the design of the coil and terminal arrangement would require an evaluation of various alternatives. Prefabricated, flat-plate conductors might have advantages over flexible cable.

Impedance Matching

With some types and sizes of d-c power sources, the cost per kilowatt of capacity is less if the voltage is several thousand volts rather than a few hundred volts. This voltage may be higher than desired for charging a storage coil. In such a situation, one might consider using an inductance coil having multiple windings which could be connected in series for charging and in parallel during discharge.

Fig. 6 is a switching arrangement which has been used at the University of Michigan. In this system, switches S_1 and S_2 are closed during charging and the two windings are series connected. When S_1 is opened, the two rectifiers cause the two windings to shift to a parallel connection, and then when S_2 is opened, the energy is delivered to the load.

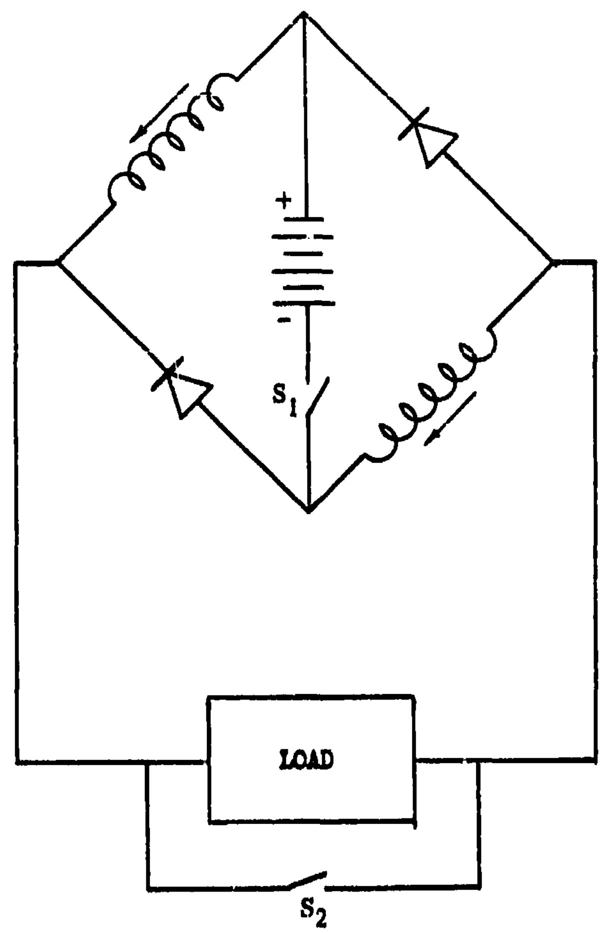

Fig. 6. Switching arrangement for charging windings in series and discharging them in parallel

Fig. 7 illustrates one of the various possible switching systems for "n" windings and "n" loads. During charge, the "A" switches are closed, and the "B" switches are open. Then, the "B" switches close as the "A" switches open. Then, the "B" switches open and transfer power to the multiple loads. The total number of switches could be reduced at a price of having some of the loads operating at a high voltage with respect to ground potential.

Fig. 8 is a photograph of a transformer-type, impedance-matching, energy-storage coil built at the University of Michigan and described in Ref. 3. This coil has a secondary winding consisting of aluminum sheets interleaved between the layers of the primary winding. A current of 4400 amperes in the primary stores 155,000 joules of energy in the magnetic field. When this current in the primary winding is interrupted, current pulses up to a half megampere are produced in the load connected to the secondary.

University of Michigan, Six-Megajoule Coil

Fig. 9 is a photograph of a 6-megajoule storage coil built for Hotshot-wind-tunnel usage. The d-c charging power comes from the Allis-Chalmers unipolar generator and flywheel, shown in the lower left of the photograph. In operation, the generator and flywheel are run up to a speed of 10,000 rpm with no field excitation on the generator. The flywheel kinetic energy storage is 20 megajoules. When the generator field excitation is applied, the coil current builds up to 3×10^5 amperes in about 3 seconds, and 6 megajoules are stored in the coil.

The coil has an inductance of 120 microhenrys, a d-c resistance of 47 micro-ohms, and a time constant of 2.5 seconds. At full current, the magnetic pinch pressure in the center of the winding is less than 4 atmospheres. Two-inch-diameter, polyethylene-insulated, stranded, aluminum cables are used for the windings. The

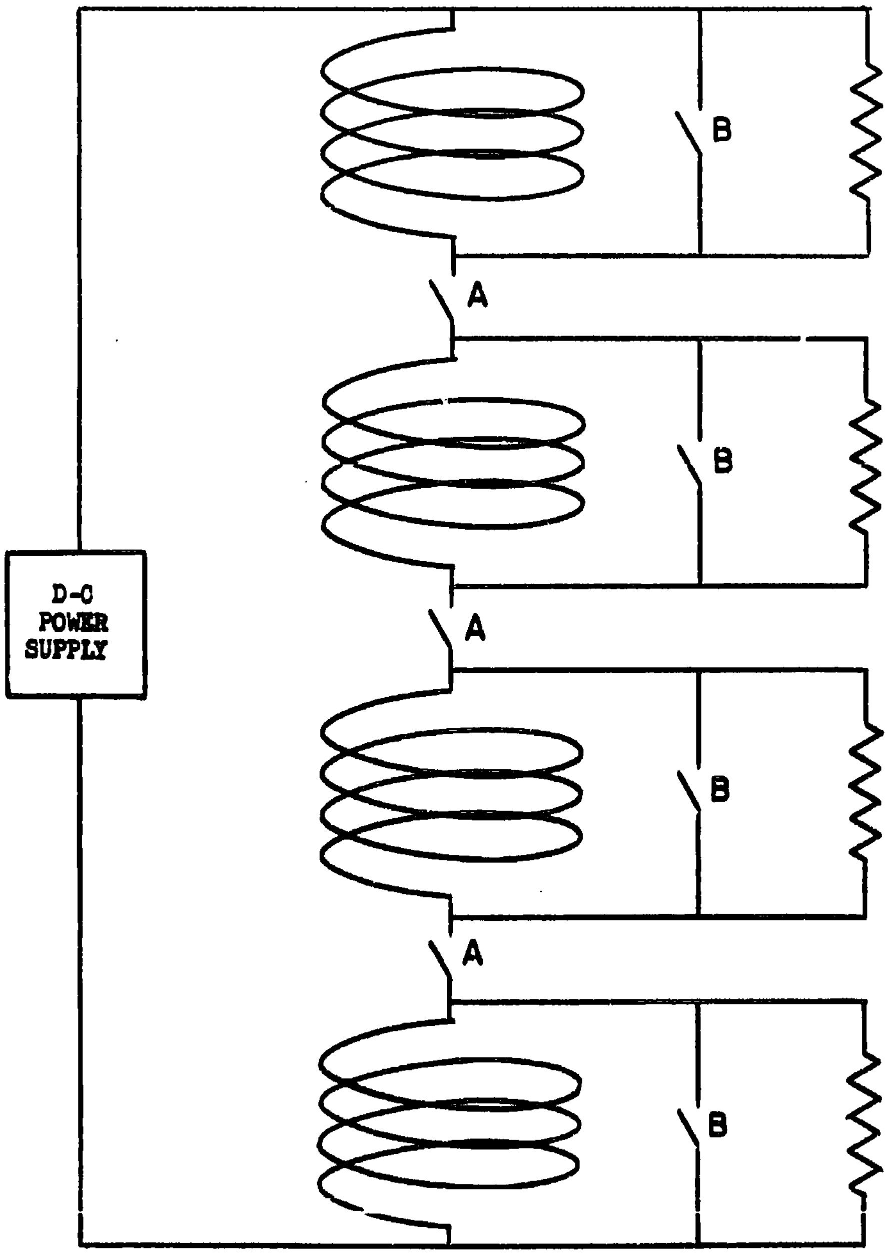

Fig. 7. Multiple-winding coil used with multiple loads

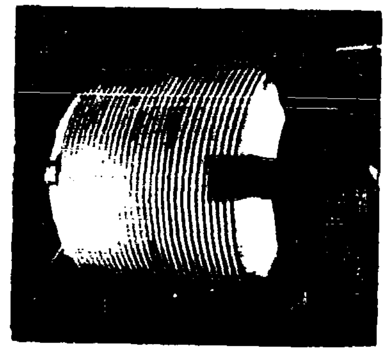

Fig. 8(a). Photograph of transformer-type energy-storage coil

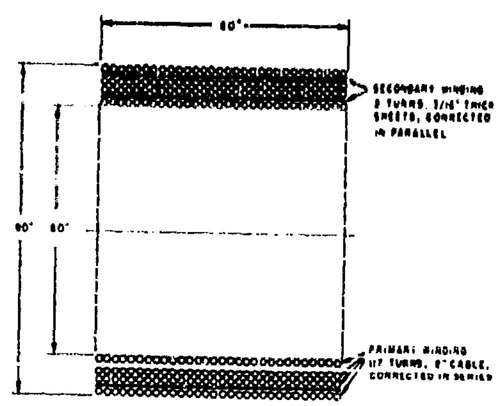

Fig. 8(b). Cross section of energy-storage transformer

Fig. 9. Six-megajoule energy-storage coil

winding consists of 26 of these cables, all connected in parallel and making a total of 6 turns around the coil. The 15,000 pounds of aluminum cable cost approximately $9,000. Heavy, oak timbers are used for most of the framework supporting the coil and terminals. Connection between the generator and coil is by means of the heavy, aluminum bus bars shown in the photograph.

The use of many parallel-connected cables in the coil winding results in energy loss due to circulating eddy currents. The effective resistance of the winding, during discharge, is much larger than the d-c resistance and results in substantial energy loss. The magnitude of the energy loss depends on factors such as pulse length and interstrand resistance which are beyond the scope of this paper. In this case, calculations based on the worst possible assumptions indicated an energy loss equivalent of 20% of the stored energy. After considering the cost of reducing this loss by various stranding and transposing methods, it was found to be more economical to accept

the loss than to accept the expense of reducing it. Compensating for the loss with extra flywheel capacity was cheaper than resorting to a more expensive coil design.

Acknowledgment

Messrs. R. C. Walker, W. N. Lawrence, and J. W. Robinson contributed to the design criteria given in this paper.

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10^8 JOULE INDUCTIVE ENERGY STORAGE SYSTEM

M. D. Horton

General Electric Company

INTRODUCTION

The General Electric Company has furnished a complete energy storage system for a 10^8 joule arc power supply. This system was functionally specified by the Government; however, the details of its design and construction were the responsibility of General Electric Company. It was designed and constructed complete with buildings, installation and testing on a fixed price, guaranteed performance contract. The installed cost to the Government was 2.3 cents per joule of electrical energy delive 'ed to the load.

The system has been in successful operation for approximately one year since its acceptance by the Government.

ARC LOAD

The purchaser's load consists of an arc chamber being used to heat air for a hypersonic wind tunnel. The arc chamber contains two tungsten electrodes that are shorted together by a device (located inside the arc chamber) which opens approximately 30 milliseconds after the current is transferred to the electrode circuit.

When the purchaser's short circuiting device opens, the resulting arc between the electrodes has an initial current of one million amperes and initial voltages as high as 20,000 volts. The energy of the power supply is released in the arc in approximately 10 milliseconds.

ARC POWER SUPPLY SCHEMATIC

Figure 1 shows a simplified schematic diagram of the arc power supply system. The purchaser's arc load has an internal shunting device (described above) which will be

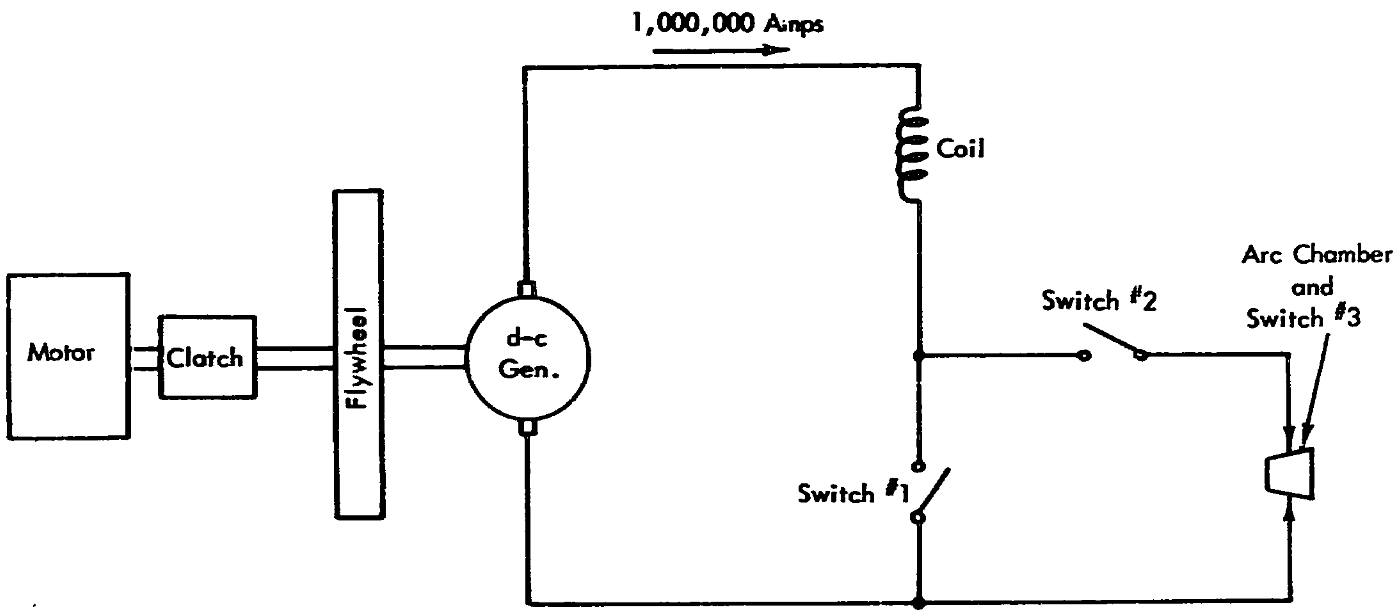

Fig. 1. Simplified schematic of 10^8-joule inductive energy storage system

called Switch #3. This device is closed until approximately 30 milliseconds after the power supply current has been transferred to the load electrodes.

Energy is stored in two stages. The first stage of energy storage is mechanical and consists of a flywheel system storing approximately 7×10^8 joules of energy and design speed. This flywheel system is accelerated from rest in period of 15 minutes by electric motors requiring approximately 2200 KW of power from the electric utility system.

The flywheels are connected to d-c generators of the acyclic (homopolar) type.

Switch #1 and Switch #2 are initially open, and field current is applied to the d-c generators to cause their terminal voltage to be 90 volts.

Switch #1 is then closed and the current in the energy storage reactor rises to one million amperes in approximately 5.5 seconds. When the current in the energy storage reactor reaches one million amperes, the electromagnetic energy stored in the field of this reactor is 10^8 joules, and the flywheels have been slowed down to approximately 60% of their initial speed and have delivered 64% (approximately 4.5×10^8 joules) of energy to the shaft of the d-c generators. The difference between the energy released by the flywheels to that stored in the energy storage coil has appeared as resistance loss in the d-c generator, the connecting cables and bus-work, and in the energy storage reactor.

When the current reaches one million amperes in the coil, Switch #2 is closed and Switch #1 is opened. This transfers the million amperes to the purchaser's arc chamber and its associated Switch #3. Approximately 30 milliseconds later, Switch #3 opens and the arc resistance is inserted in the circuit.

The initial arc voltage can be as high as 20,000 volts. At this voltage and at an initial current of one million amperes, the initial power in the load is 20 million KW.

called Switch #3. This device is closed until approximately 30 milliseconds after the power supply current has been transferred to the load electrodes.

Energy is stored in two stages. The first stage of energy storage is mechanical and consists of a flywheel system storing approximately 7×10^8 joules of energy and design speed. This flywheel system is accelerated from rest in period of 15 minutes by electric motors requiring approximately 2200 KW of power from the electric utility system.

The flywheels are connected to d-c generators of the acyclic (homopolar) type. Switch #1 and Switch #2 are initially open, and field current is applied to the d-c generators to cause their terminal voltage to be 90 volts.

Switch #1 is then closed and the current in the energy storage reactor rises to one million amperes in approximately 5.5 seconds. When the current in the energy storage reactor reaches one million amperes, the electromagnetic energy stored in the field of this reactor is 10^8 joules, and the flywheels have been slowed down to approximately 60% of their initial speed and have delivered 64% (approximately 4.5×10^8 joules) of energy to the shaft of the d-c generators. The difference between the energy released by the flywheels to that stored in the energy storage coil has appeared as resistance loss in the d-c generator, the connecting cables and bus-work, and in the energy storage reactor.

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The initial arc voltage can be as high as 20,000 volts. At this voltage and at an initial current of one million amperes, the initial power in the load is 20 million KW.

The system is capable of being fired within 15 minutes after an extended period of idleness. It can be operated at 30-minute intervals at full energy level.

The system is fully automatic in its operation and is remotely controlled from a separate building. The entire system may be started, fired and shut down from the remote control location.

The system has been tested to peak currents of 1.25 million amperes, at which time the energy stored in the energy storage reactor was approximately 1.5×10^8 joules.

DESCRIPTION OF SYSTEM COMPONENTS

Energy Storage Reactor

The energy storage reactor is an air-core, copper coil having a vertical axis. It was factory wound and shipped as one piece to the site. Its characteristics are tabulated below:

200 micro-henries inductance
6-second time constant
1,000,000 amperes
10^8 joules
20,000 volts peak discharge voltage
12 ft. outside diameter
5 ft. high
5 ft. diameter central bore
80,000 gauss flux density at central axis, central plane
110,000 lbs. approximate weight

Flywheel Motor-Generator Sets

Two identical flywheel motor-generator sets are employed. Each consists of the following:

1- 1000-hp, 6600-v, 3-phase, 60-cycle, 1750-rpm squirrel-cage induction motor.

1- Water-cooled eddy current clutch rated for 1500 hp maximum slip loss.

1- Energy storage flywheel rated 3.5×10^8 joules at 1800 rpm.

2- Acyclic d-c generators connected in series. Each generator is rated 45 v, 550,000 amp peak, 1800 rpm. The acyclic generators are completely sealed with a dry nitrogen atmosphere and employ a liquid-metal current collection system using metallic sodium and potassium. If these generators were to be given a continuous rating, they would each be capable of delivering 6,750 kw, 45 v, 150,000 amp.

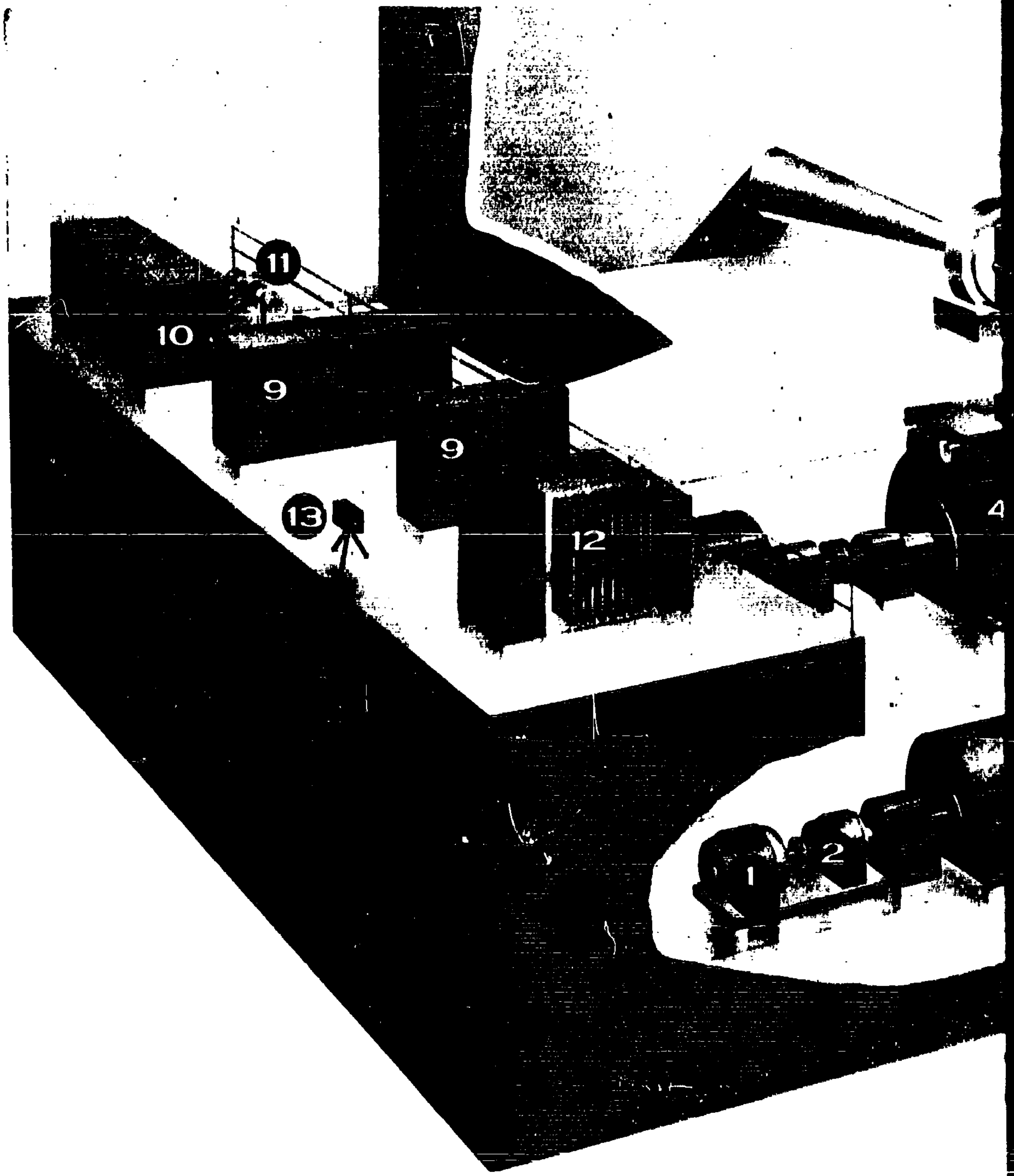
Switch #1

This switch actually consists of four 3-pole power circuit breakers connected such that all 12 poles are in parallel. These breakers are slightly modified versions of standard a-c power circuit breakers. The combination opens when it is carrying one million amperes or approximately 83,000 amp per pole. After the poles have been opened and the arc has been extinguished, the device must withstand approximately 20,000 volts during the load pulse.

The 12 poles have been carefully connected in the circuit such that they divide current and arc-energy approximately equally. The total arcing energy in the 12 poles of these breakers when interrupting one million amperes is approximately 2×10^6 joules. This is approximately 2% of the energy which is delivered to the load. The current interruption takes place in approximately ten milliseconds.

Interconnecting Bus and Cable

The coils, generators and load are interconnected by a system of cables and bare copper bus bar. The charging circuit connecting the generators to the coil has 48- 1/4" x 12" copper bus bars in parallel per pole. Where cable is used in this same circuit, it consists of 36- 5,000,000 circular-mil insulated cables in parallel per pole. The resistance of the bus and cable system is approximately half the resistance of the energy storage coil, and hence the net time constant of the coil circuit is approximately 4 seconds (the coil has a time constant of 6 seconds measured at its terminals).



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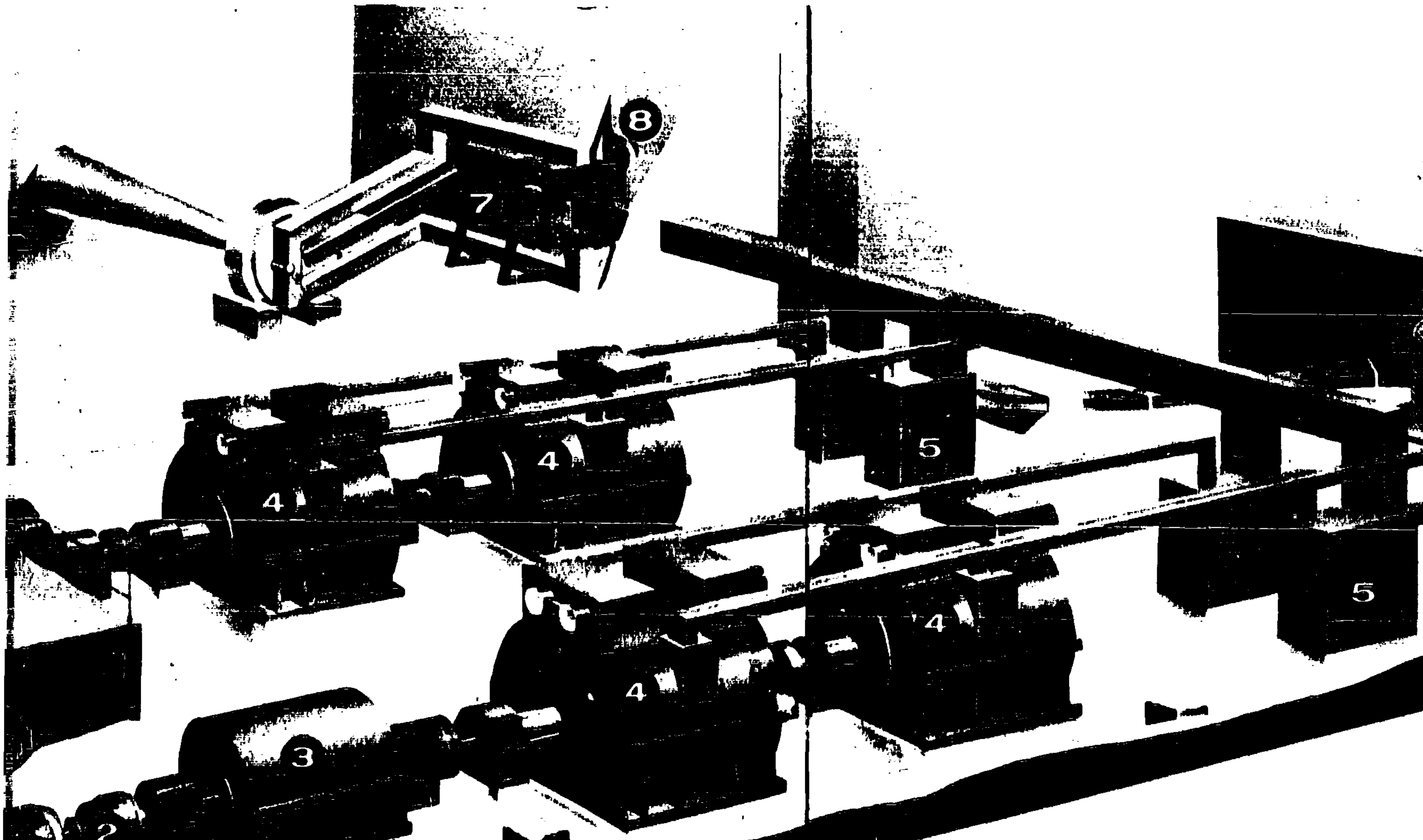
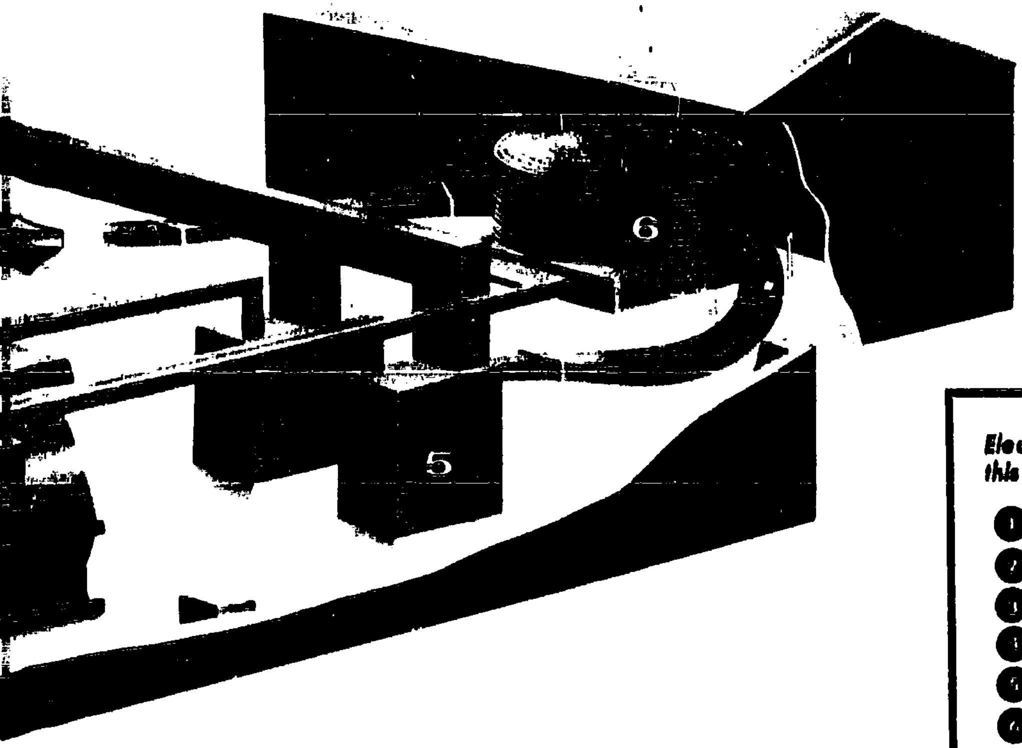


INDUCTIVE ENE
SYSTEM FOR "HOT SHO

Where extremely large amounts of stored electrical energy joules in a typical large "hot shot" tunnel), the energy surrounding a large coil. This type of energy storage p large installations where exceptionally fast discharge time shown, flywheel motor-generator sets supply energy to discharged into the tunnel arc chamber.

2



INDUCTIVE ENERGY STORAGE
TEM FOR "HOT SHOT" TUNNELS

xtremely large amounts of stored electrical energy must be provided (100 million a typical large "hot shot" tunnel), the energy is stored in the magnetic field ling a large coil. This type of energy storage provides maximum economy for tallations where exceptionally fast discharge times are not critical. In the system lywheel motor-generator sets supply energy to the coil. This energy is in turn ed into the tunnel arc chamber.

Electrical equipment for this system includes:

1. INDUCTION MOTOR
2. EDDY-CURRENT COUPLING
3. FLYWHEEL
4. ACYCLIC GENERATORS
5. TRANSFER SWITCHES
6. STORAGE COIL
7. LOAD ISOLATING SWITCH
8. SPECIAL PROTECTIVE GAP
9. MOTOR CONTROL CENTER
10. METAL-CLAD SWITCHGEAR
11. AMPLIDYNE MG SETS
12. LOAD CENTER SUBSTATION
13. CLOSED-CIRCUIT TELEVISION

3

Fig. 2. 10^8-joule inductive energy storage system: cutaway view

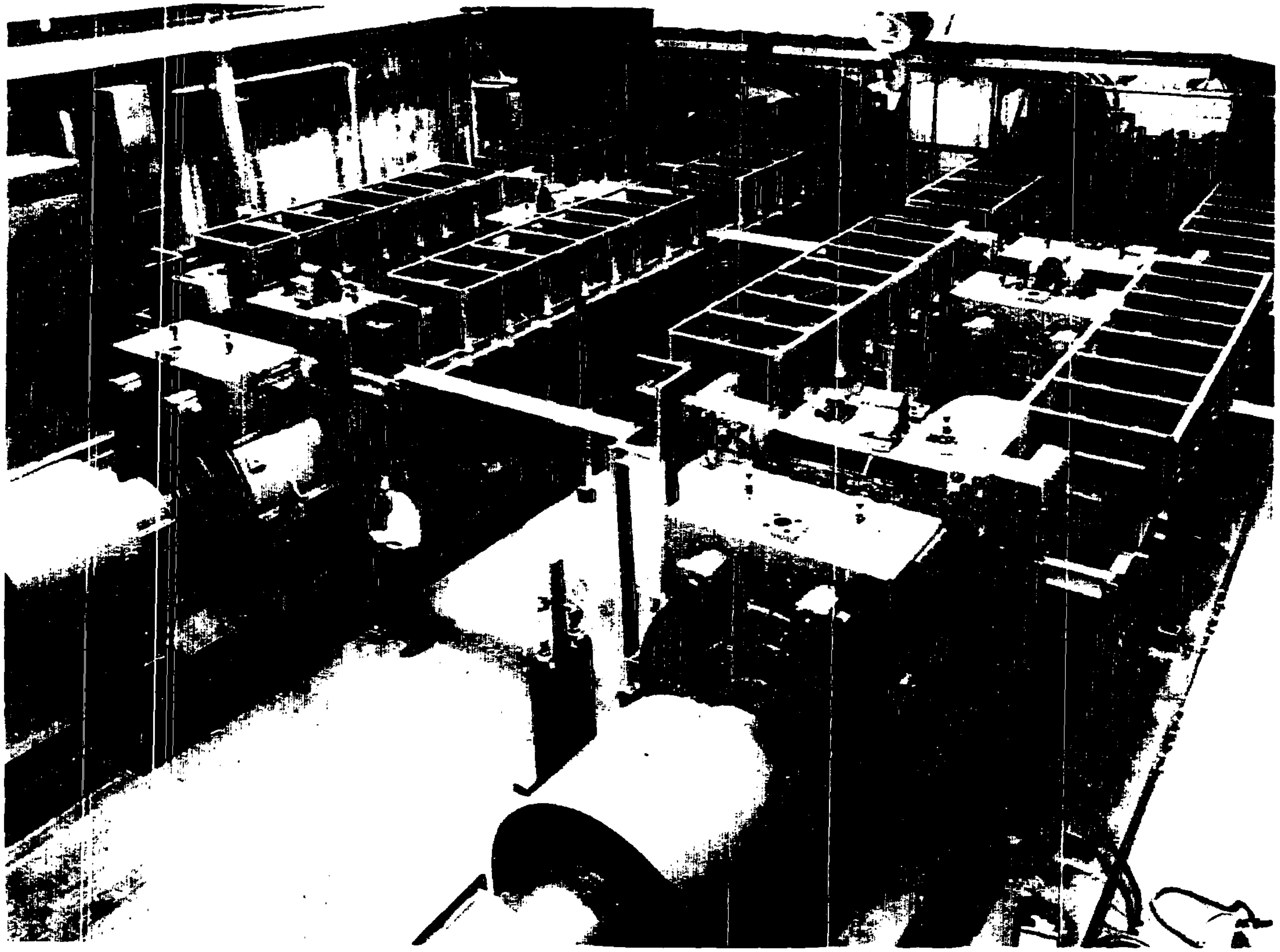


Fig. 3. 10^8-joule inductive energy storage system: four acyclic generators and 1,000,000-amp busbard

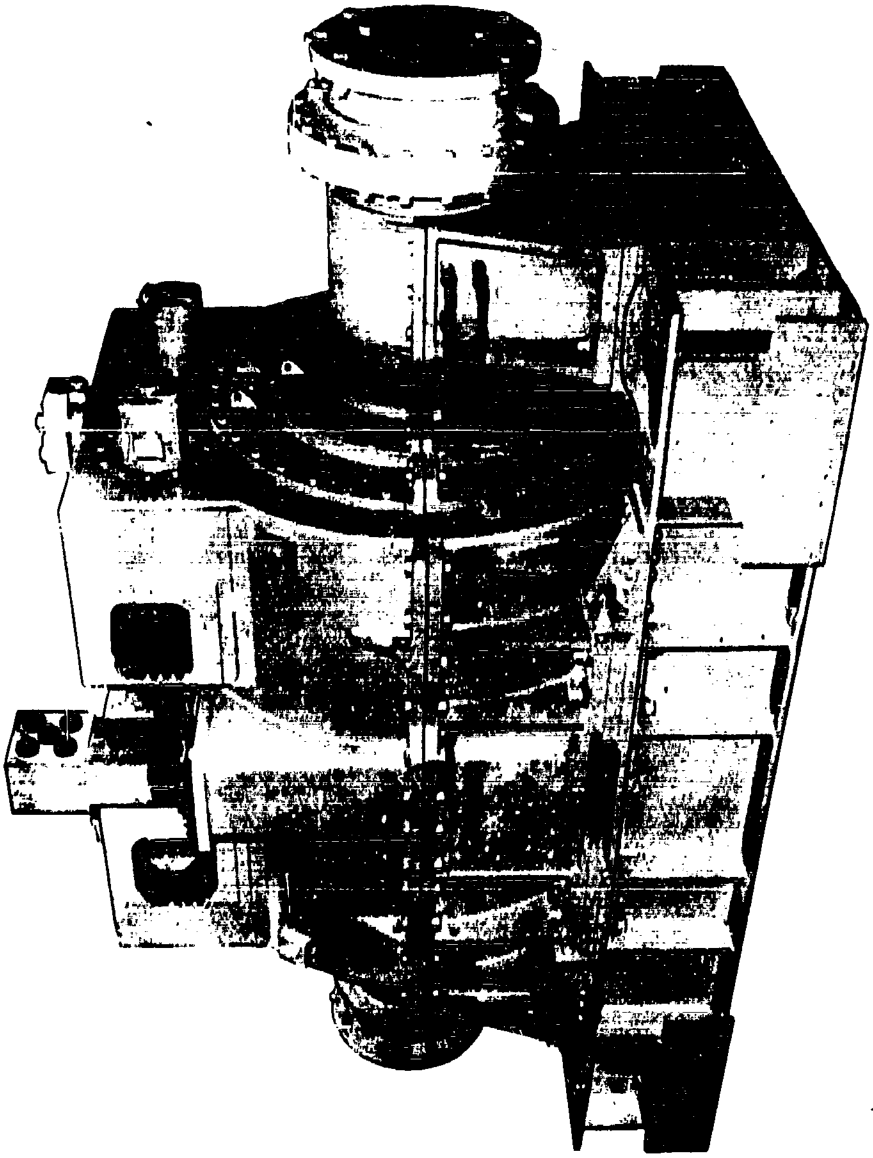


Fig. 4. Factory photograph of acyclic generator

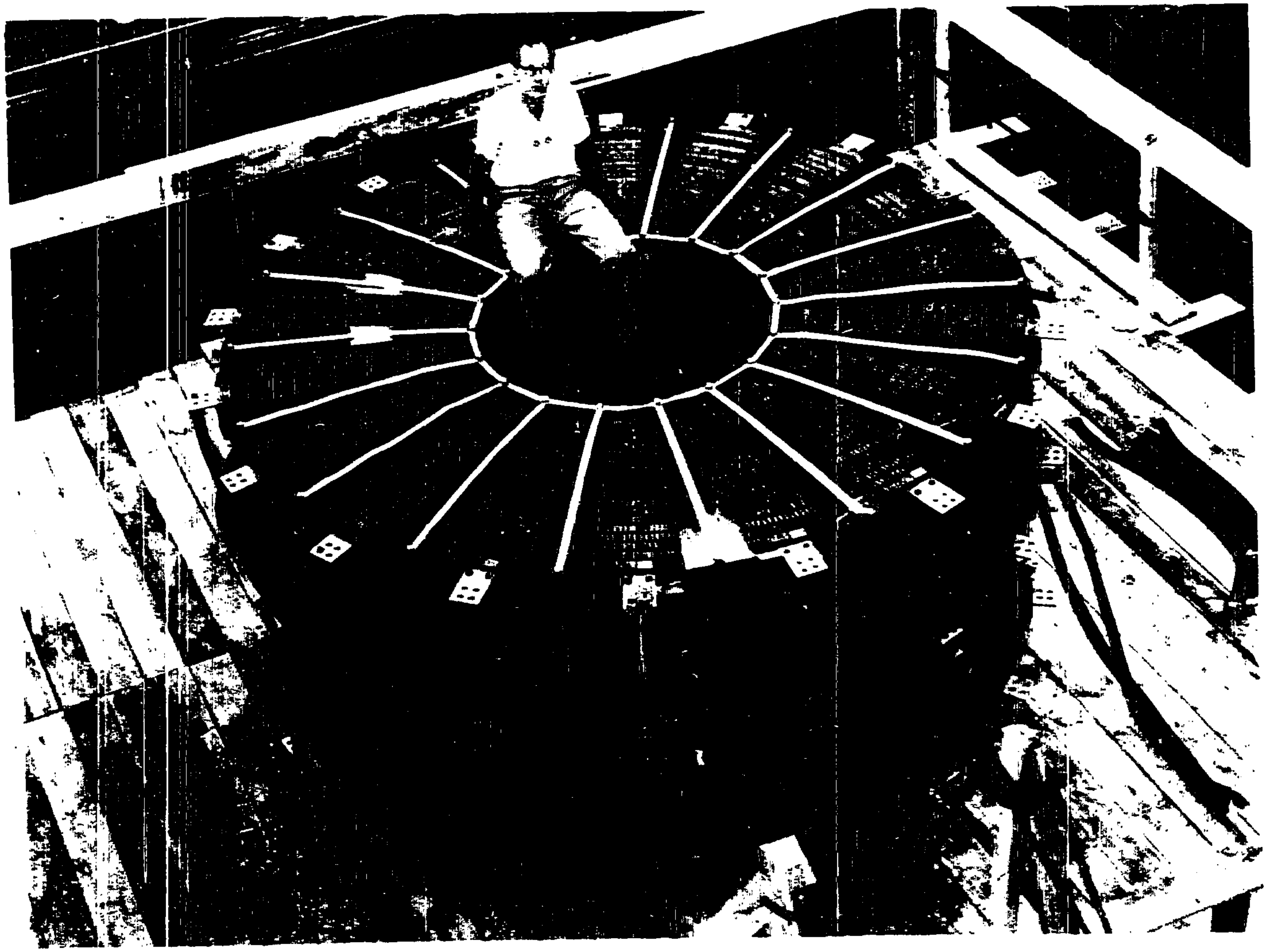


Fig. 5. 10^8-joule, 6-sec time constant energy-storage coil (Photographed during factory testing.)

CAPACITANCE AND INDUCTANCE
ENERGY STORAGE SYSTEMS AT AEDC

R. R. Walker, III

von Kármán Gas Dynamics Facility ARO, Inc.

At Arnold Engineering Development Center, there are three high energy storage systems that are currently used to drive hypersonic wind tunnels. One is a 10^6 Joules capacitance energy storage system, and the other two are 10^7 and 10^8 Joules inductance energy storage systems.

A photograph of the 10^6 Joules capacitance system is shown in Fig. 1. This system consists of a bank of 1,000 capacitators, all in parallel, each capacitor rated at 125 microfarads and 4 KV. A schematic of the system is shown in Fig. 2. The initial cost of this system was approximately $84,000.

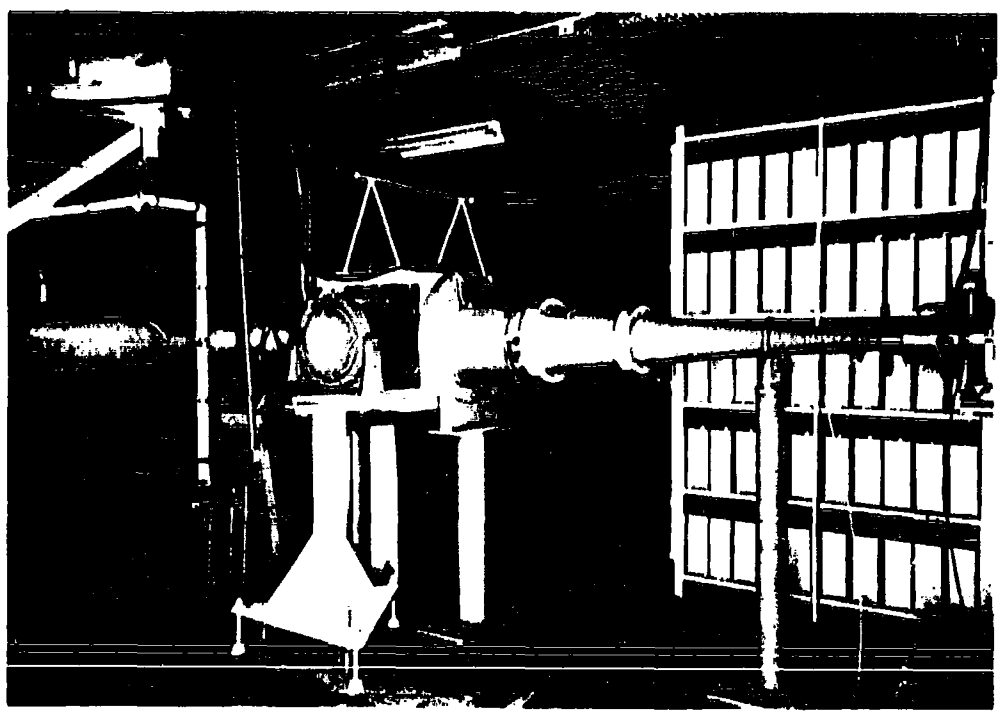


Fig. 1. 10^6-joule capacitance system

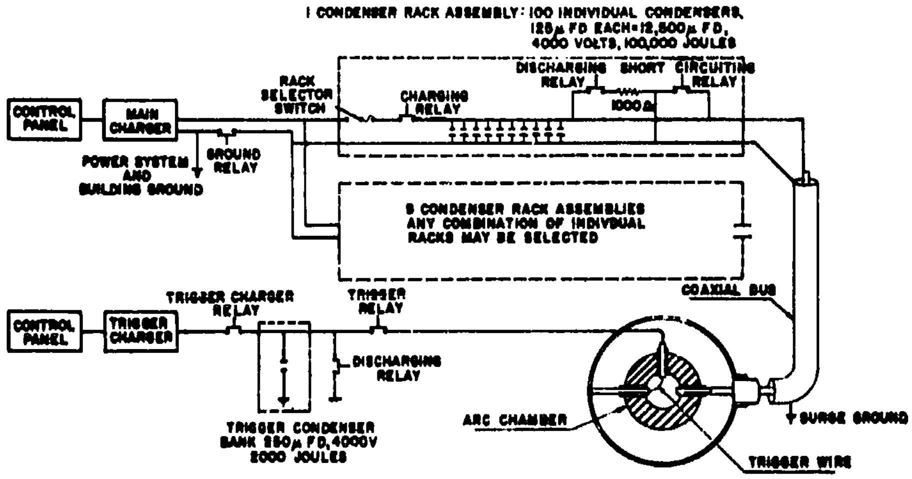


Fig. 2. Schematic of 10^6-joule capacitance system

A schematic of the 10^7-joule inductance system is shown in Fig. 3. This system consists of a unipolar generator, flywheel, energy storage coil, and associated bus and switches. The unipolar generator has a continuous rating of 80,000 amperes at 70 volts and a pulse rating of 250,000 amperes at 70 volts for short time pulses. Typical current and voltage characteristics during energy discharge are shown in Fig. 4. The initial cost of this system was approximately $380,000.

A pictorial representation of the 10^8-joule inductance system is shown in Fig. 5. This system consists of four acyclic generators, rated at 550,000 amperes at 45 volts, connected in a series parallel arrangement to deliver one million amperes at 90 volts. The system is capable of delivering 10^8 Joules to a 0.02 ohm resistive load in 10 milliseconds at 20 KV. A typical arc chamber used with the 10^8 Joules system is shown in Fig. 6. The initial cost of this system was approximately $2.3 million.

A comparison of the cost per Joule for several power supplies is shown in Fig. 7. This plot indicates that for higher energy storage systems, the inductance system would be much cheaper than the capacitance system.

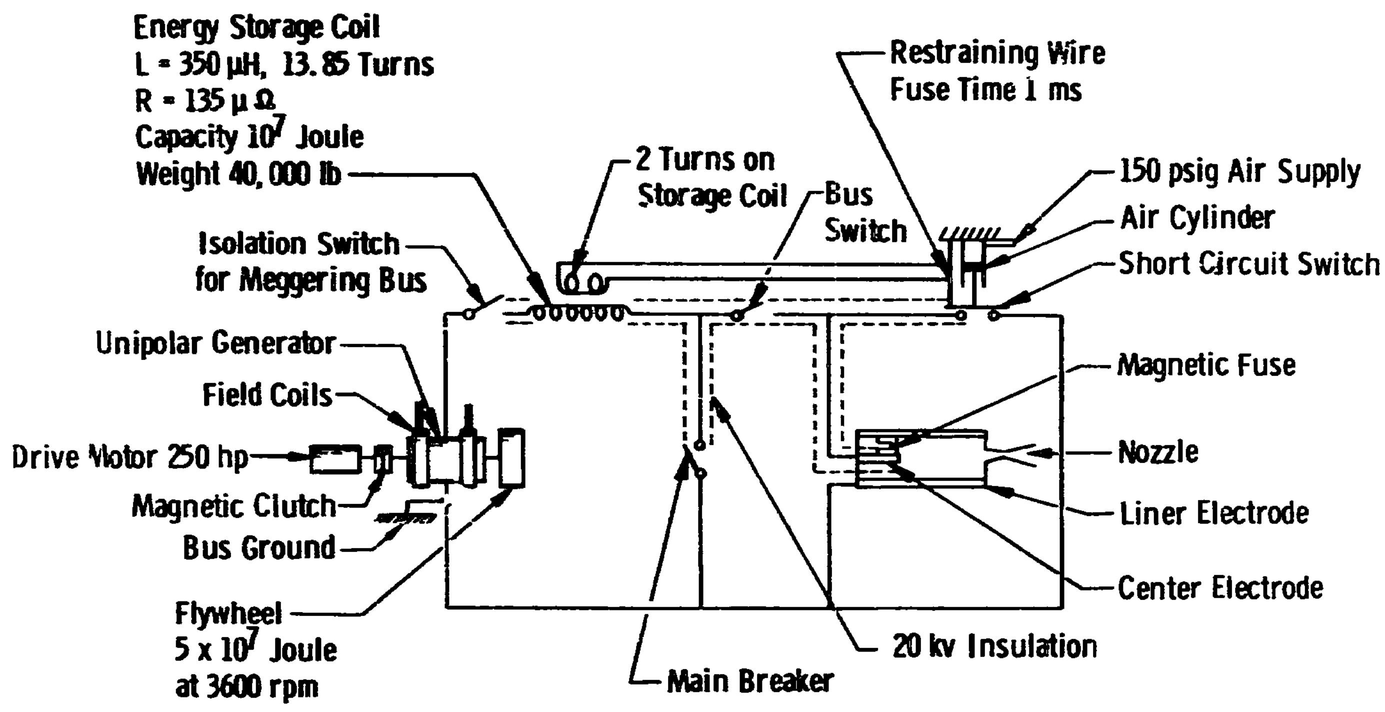


Fig. 3. Schematic of 10^7-joule inductance system

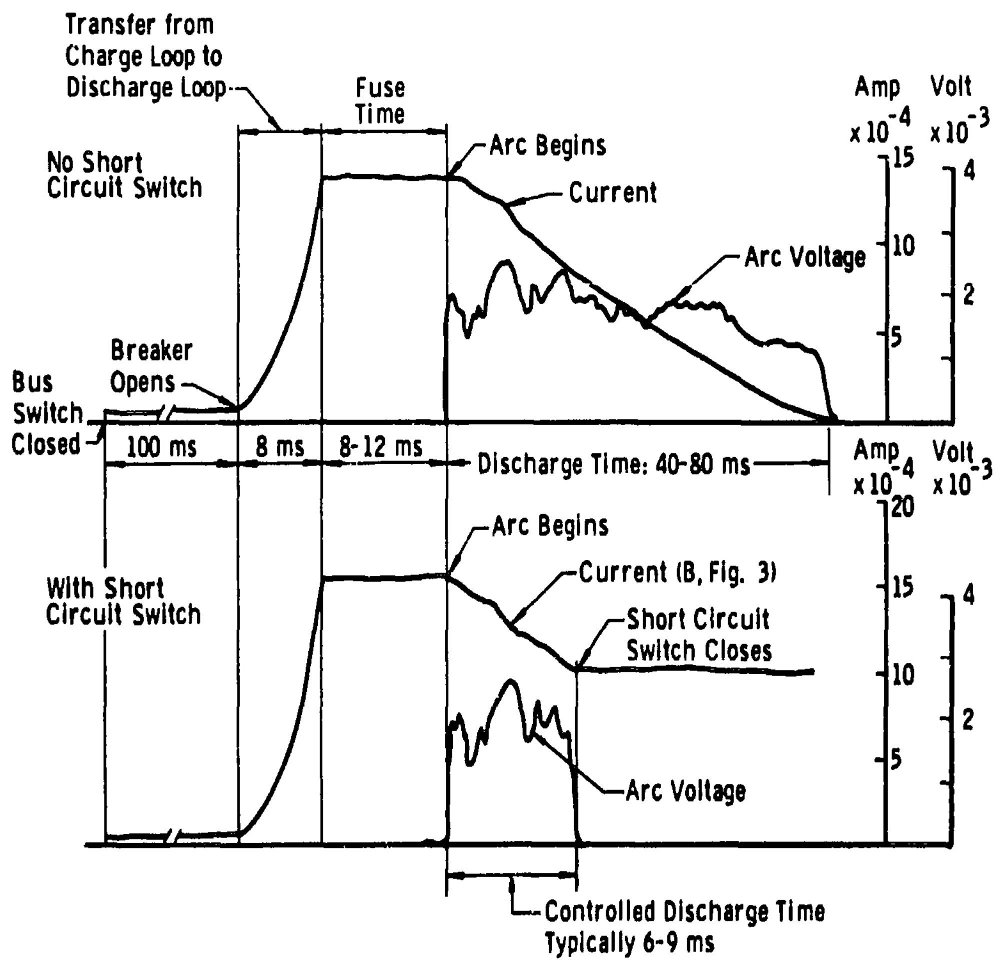


Fig. 4. Typical Current and Voltage Characteristics during Energy Discharge for 10^7 Joules Inductance System

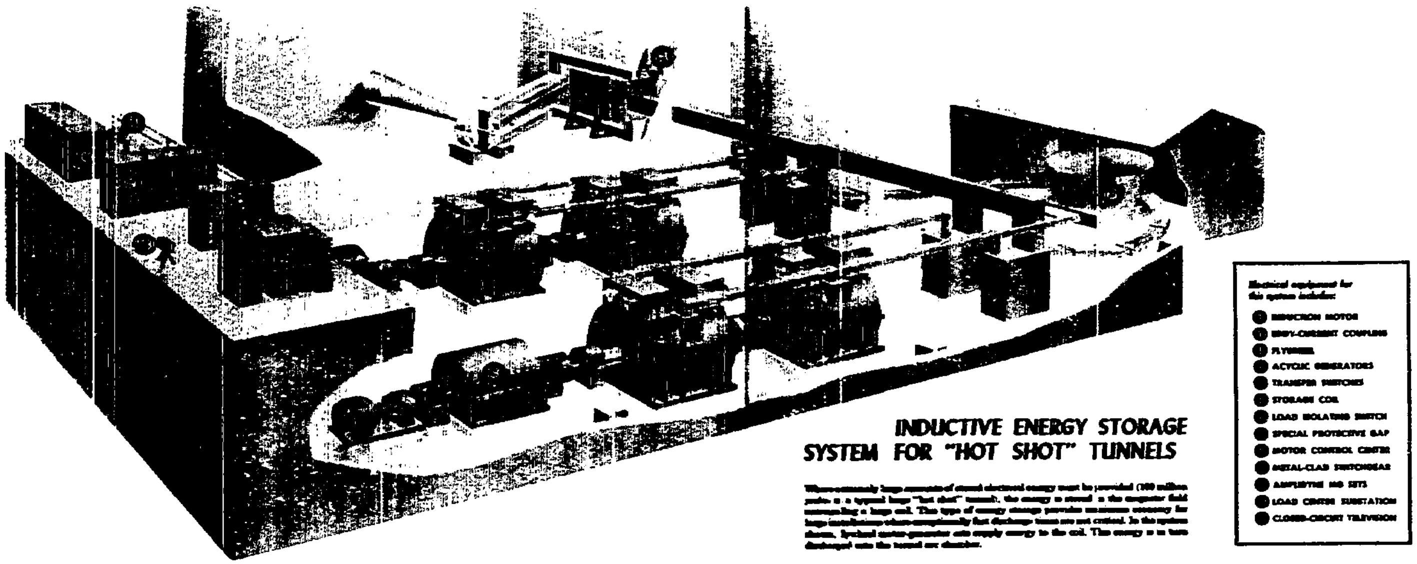


Fig. 5. 10^8-joule inductance system

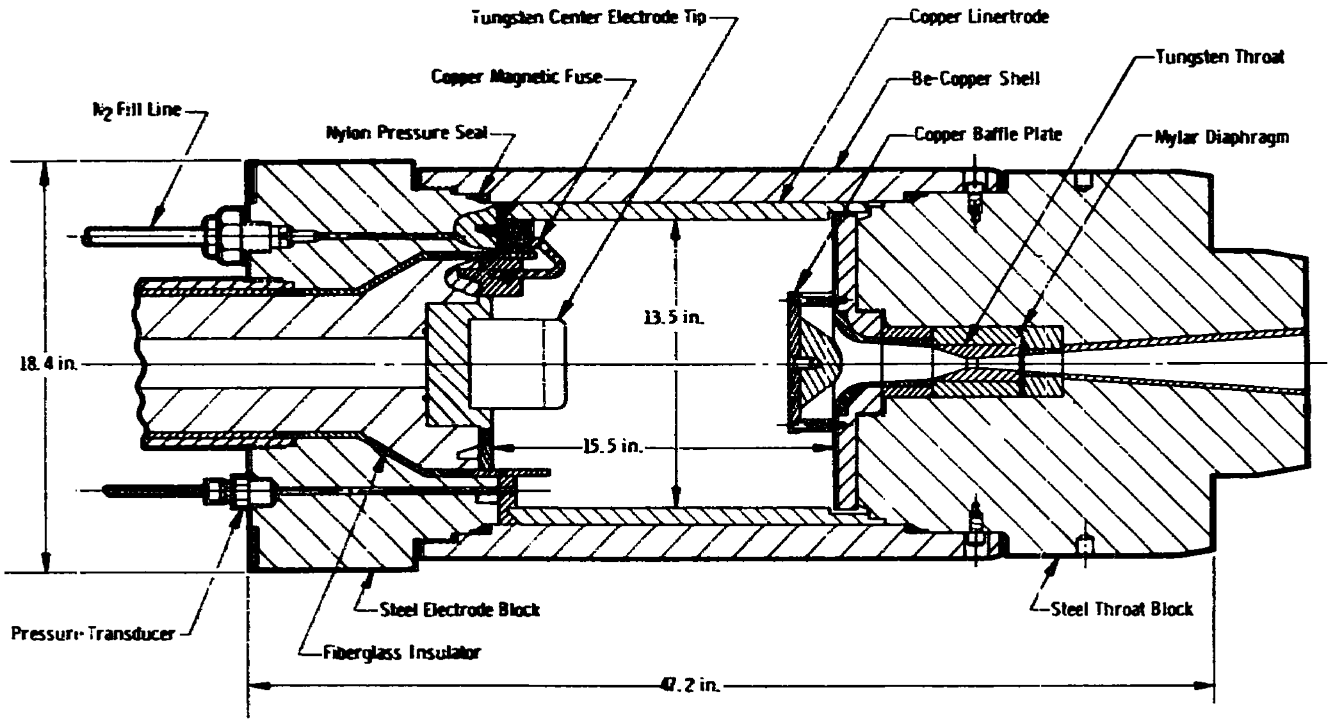


Fig. 6. Typical Arc Chamber Used with the 10^8 Joules Inductance System

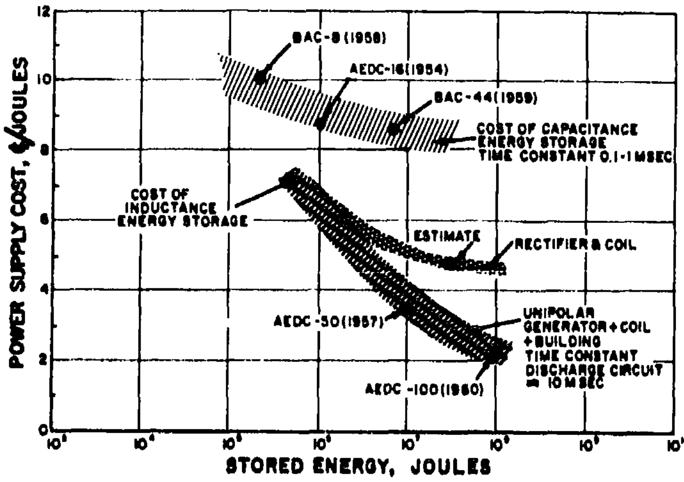


Fig. 7. Cost of Capacitance and Inductance Energy Storage

INDUCTIVE ENERGY STORAGE FOR HIGH ENERGY PULSES

L. A. Kilgore, Paul Hawkshaw, & Charles H. Church

Westinghouse Electric Corporation

Energy storage in inductors is much less expensive than capacitors, but the minumum pulse length is about 1 millisecond.

The energy stored inductively is given as

$$E = 1/2\ LI^2$$

and the time constant is L/R

where

L is the inductance in Henrys
R is the total resistance in ohms
I is the current in amperes and
E is in joules.

The output voltage given by IR, the voltage drop across the load.

For a load voltage of 10 kv and a time constant of 10^{-3} seconds, the resistance of the load is

$$R = \frac{10^5}{2E}$$

which corresponds to a current of

$$I = \frac{2E}{10}$$

For the energies contemplated, these currents would probably be much too high for one conductor. In any practical system, there would be multiple loads with subdivision in turn of the energy storage facility. Scaling up with the attendent lower cost can lead to difficulty if too large a single coil is attempted.

The optimum size depends upon the circuit time constants desired with lesser times requiring the smaller coils. The switching requirements for large inductive

stores, which must break a circuit rather than make it as in capacitors, is a problem requiring extensive research particularly if a low jitter fast clearing efficient scheme is required. The cost of the switches may exceed the cost of the energy storage facility.

Using a twenty megajoule coil with a discharge time of 10 millisecond, at an insulation rating of 25 kv as an example, the cost of the energy storage coil was about 0.5 cents per joule. A similar ten megajoule coil is shown being wound in Figure 1. The switch used to transfer the energy from this ten megajoule coil (at 100,000 amperes) is shown in Figure 2. This switch is relatively slow and may have relatively high jitter.

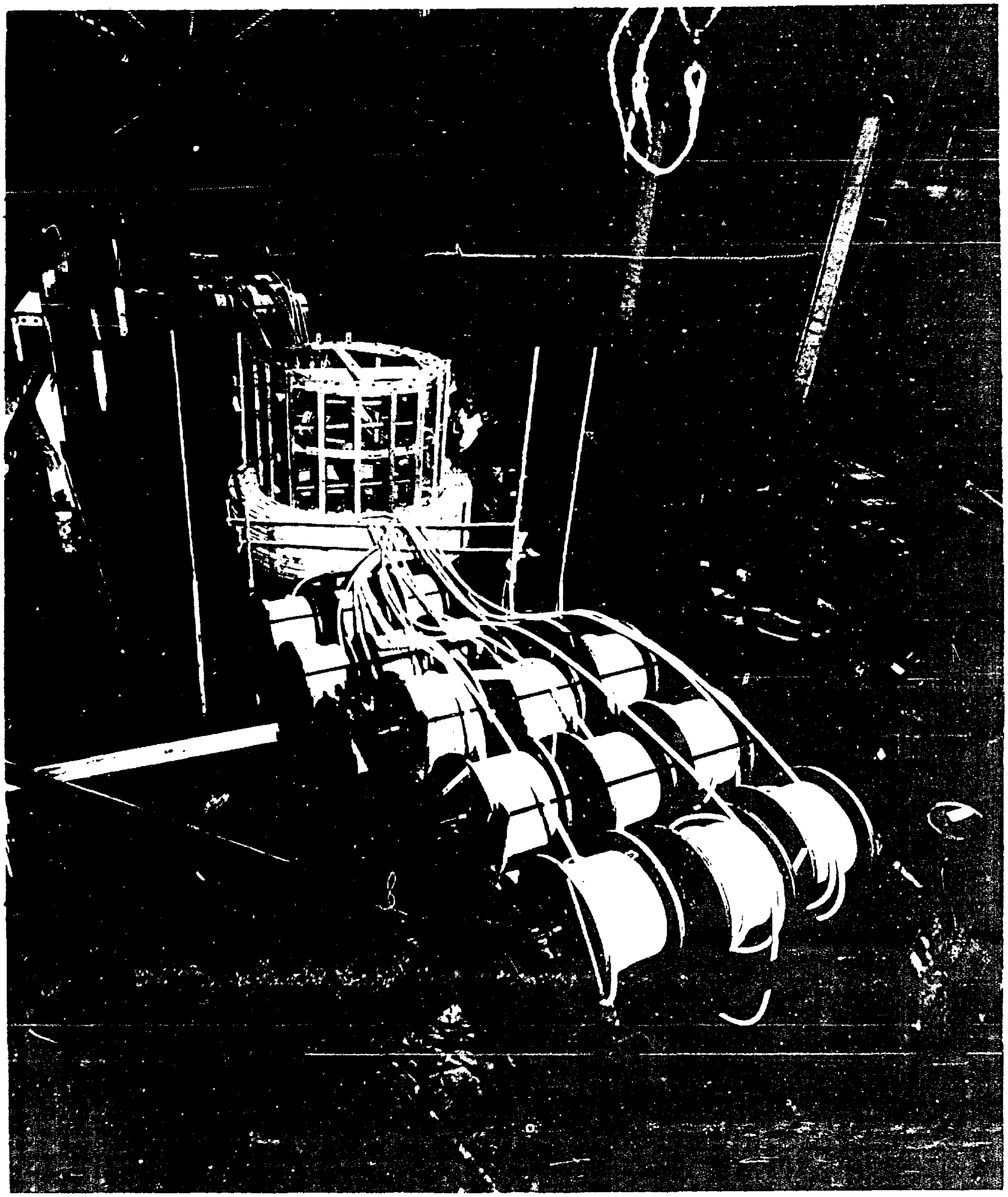


Fig. 1. 10 MJ Inductance Coil for ARO Arc Heater Being Wound at Westinghouse Sharon Works, Sharon, Pennsylvania

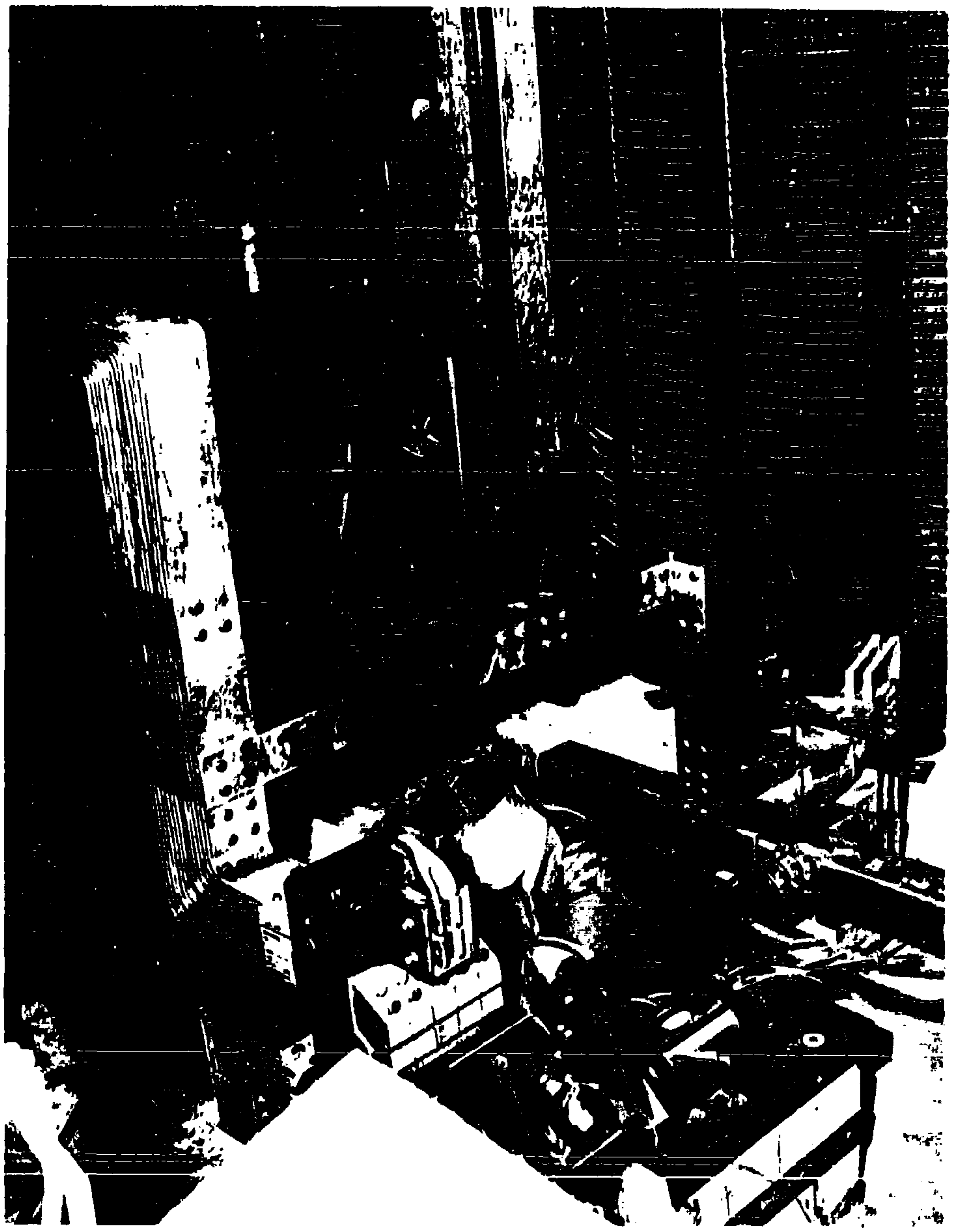


Fig. 2. Switch Used to Open Circuit of 10 MJ Inductance Coil (in rear) Westinghouse-ARO Arc Heater

SUMMARY

R. C. Hamilton

Institute for Defense Analyses

A 10^8-joule inductor has been in operation for over a year at the Arnold Air Force Development Center. Inductors of this capacity may be required in some applications. The technical feasibility of inductive energy storage of this magnitude has been demonstrated. Inductive energy storage is one of the lowest-cost energy storage methods available today. Costs for only the inductors installed at Arnold Air Force Development Center are estimated to be 4/10 and 1/10¢ per joule for 10^7 and 10^8 joule inductors, respectively. They do not, however, include an independent power source, switchgear, building, or land.

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III SUPERCONDUCTING INDUCTIVE ENERGY STORAGE

ENERGY STORAGE IN SUPERCONDUCTING COILS

FOR HIGH PULSED POWER APPLICATIONS

by

William F. Hassel

Research Assistant, Jet Propulsion Center, Purdue University

INTRODUCTION

With the recent development of high field superconducting wire, the long term storage of energy within a high inductance superconducting coil becomes a promising possibility. For many years large inductance magnetic coils have been used in laboratories in experiments requiring high energy delivery rates, up to 10^5 joules over a period of milliseconds.[1] Due to resistive losses in the coils, a large amount of power is required to maintain the current through the coil prior to discharge through the load. During discharge, the output current decreases exponentially from its steady state value in the coil to zero, for a critically damped or overdamped circuit. Such a device is ideally suited for the generation of high amplitude pulsed power, but suffers from the drawbacks of requiring a continuous high power input and of providing only a relatively low energy output. At the present time, however, by making use of "hard" superconductors, which are capable of generating intense magnetic fields with low coil weights, it becomes possible to store energy in the magnetic field created by the coil without any additional expenditure of energy, once the current through the coil is established. After such a coil is energized and its input leads short-circuited, the current will continue to flow without diminishing for an indefinite period, since there are no resistive losses. At any given time a portion of the energy stored in the coil may be withdrawn through a load switched into the circuit to provide a very high peak power.

The principal disadvantage of the superconducting inductance coil is its requirement for a liquid helium bath to maintain its temperature in the vicinity of $4^{\circ}K$. With the superinsulations available today, however, the helium refrigeration requirements do not appear excessive.

An optimization of the superconducting coil for energy storage shows that the energy per unit weight exceeds that of the best high performance batteries. This high energy storage density is realizable only in coils of many meters diameter. Consequently, high storage density is accompanied by high total energy. The high energy capability combined with the characteristic pulse discharge appear to make the superconducting coil ideally suited to the requirements for high pulsed power. It is the purpose of this study to determine the characteristics of a superconducting coil pulse power source necessary to satisfy these requirements.

CHARACTERISTICS OF SUPERCONDUCTING WIRE

There are now commercially available two types of superconducting wire suitable for producing high field coils. One is produced by packing three parts niobium to one part tin in powder form into a niobium tube, drawing the tube into a fine wire, winding into the desired coil configuration, and then reacting the powdered core in an oven to form the superconducting Nb_3Sn intermetallic alloy. After reacting the wire becomes very brittle. The other material, which is in somewhat wider use for producing solenoids, is the alloy Nb-25 at.% (atomic percent) Zr, which has both high ductility and strength. It is possible to produce a ductile Nb_3Sn wire by plating the Nb_3Sn upon a base wire. This type has not been considered in the present study because it is not yet available in large quantities.

The current capacity of a superconductor at a fixed temperature is a function of its physical properties and the applied magnetic field. There exists a critical field above which the material loses its superconductivity at a given current density and temperature. This results in an inverse relationship between current density and applied field. A convenient temperature for operation is that of liquid helium at atmospheric pressure, 4.2° K. The superconducting properties of Ni-Zr wire are particularly susceptible to cold working, dictating the necessity for drawing the wires to very small diameters of the order of 0.010 in. At best this wire exhibits a high field limit of 9.0 webers/sq. m. at low current densities, which is considerably below the limit for Nb_3Sn. Nb-Zr wire appears to exhibit a saturation current when wound into coil form which is not evident in small sample tests, that is, wire which can carry, say, 100 amperes in low applied fields may be able to carry only 20 amperes over a wide range of magnetic field strengths when wound into a solenoid.[2] This effect can be avoided in Nb_3Sn coils. Still another disadvantage of Nb-Zr is the apparent necessity for "training" the material by repeated applications of voltage to accept an increasingly higher current for a given magnetic field.[3] It would be well to avoid such effects in a device in which transients are inherent in the normal mode of operation. It herefore appears that Nb_3Sn is by far the more suitable material for a high power, pulse discharge system. Furthermore, it was shown in Reference 4 that the Nb_3Sn system is capable of a considerably higher energy storage density than is the Nb-Zr system. The variation of current density with applied magentic field for Nb_3Sn is shown in Figure 1.[5] The indicated current density is that in the superconducting core, which is of 0.005-in diameter. The wire diameter including niobium cladding is 0.010-in.

DESIGN OF THE PULSED POWER SOURCE

The general design features of the proposed inductance coil are shown in Fig. 2. The coil would be composed of a series of separate windings, each of which would be wound of many strands in parallel of 0.010-in Nb_3Sn wire. The parallel strands would be necessary to provide the desired current output per winding. Preferably the coil should be constructed so that the mutual inductance between a given winding and any other winding is a constant. The wire should be plated with copper or other non-superconductor to provide good heat transfer properties and effective electrical insulation. A 0.001-in thick sheet of Mylar can be placed between layers of wire to guard against leakage currents and the resultant joule heating as a result of the voltage gradients between windings during discharge. The ends of each winding are connected to the contacts of the switch shown in the figure in such a way that each winding is either short-circuited through the switch, connected to the external load, or open-circuited. As the switch actuator is advanced upward, the shorting bar breaks contact with the lower coil circuit, and the coil current is forced to flow through the external load, which results in a decay of the current to zero and a delivery of energy to the load. Further advancement of the actuator disconnects the discharged winding from the circuit and diverts the energy of the next winding into the load.

All the switch components must be made of superconducting materials. As the magnetic field in the vicinity of the switch could be quite low compared to that within the coil, any of a wide variety of "soft" superconductors with low magnetic field limits, such as pure niobium, could be used for the switch. Although a mechanical superconducting switch has not

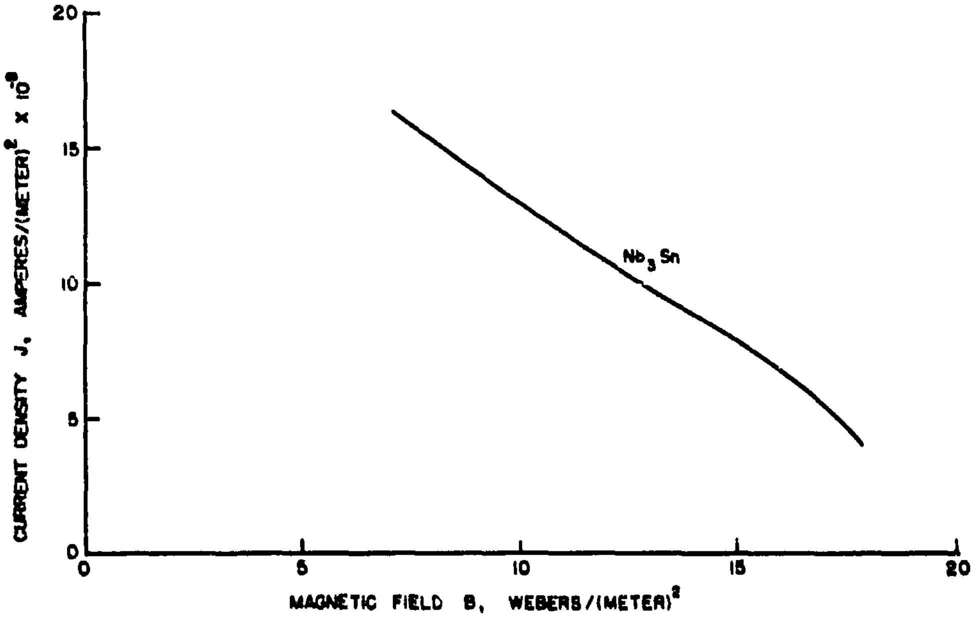
CURRENT DENSITY J, AMPERES/(METER)^2 x 10^9
MAGNETIC FIELD B, WEBERS/(METER)^2
Nb_3Sn
0
5
10
15
20

Fig. 1.

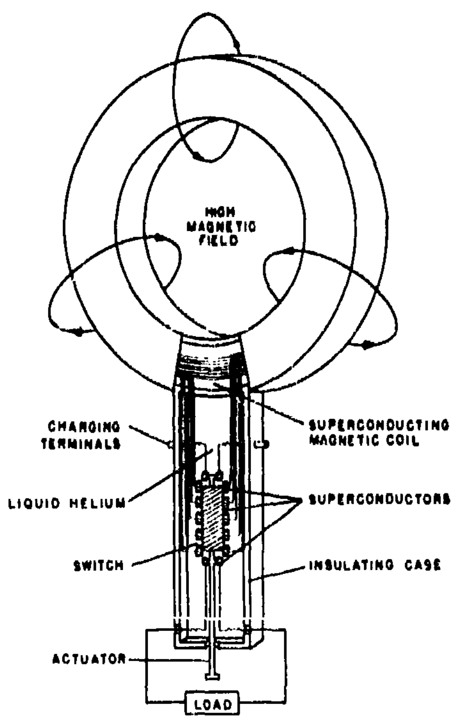
HIGH MAGNETIC FIELD
CHARGING TERMINALS
SUPERCONDUCTING MAGNETIC COIL
LIQUID HELIUM
SUPERCONDUCTORS
SWITCH
INSULATING CASE
ACTUATOR
LOAD

Fig. 2.

yet been made, there is apparently no difficulty in maintaining a superconducting contact between clamped surfaces.[2]

All components, including the coil, switch, and output leads are bathed in liquid helium in order to maintain superconductivity. The entire device is enclosed within a titanium alloy case having a thermal liner of evacuated superinsulation to inhibit helium loss.

The device would be initially energized by moving the switch to its lowermost position, where the charging contacts are in the circuit of the lowermost coil. A d-c power source capable of supplying a current at least equal to that desired in any given winding is then attached to the input power terminals. When the current in the first winding reaches the desired value, the actuator is advanced so that the current through the first winding now passes through the shorting bar and the next winding is being energized. In this manner the entire device can be energized by a comparatively low output power supply.

DETERMINATION OF ENERGY STORAGE CAPABILITY

The energy, E, stored in a coil of inductance, L, carrying a current, I, is given by

$$E = \frac{1}{2} LI^2.$$

This may be expressed as energy per unit volume:

$$\frac{E}{V} = \frac{1}{2} \frac{L}{V} I^2$$

Assume a coil of rectangular cross section, for which a is the average radius, b the length, and c the winding thickness. The standard formula for inductance of such a coil is [6]

$$L = \frac{a^2 n^2}{b} \left[K - 0.318 \frac{c}{a} (0.693 + B_s)\right] \cdot 10^{-6} \text{ henries,}$$

where K and B_s are tabulated in the reference as functions of b/a and

b/c respectively. The reference volume of the coil is assumed to be that volume occupied by the windings.

$$V = 2\pi\ abc$$

Since the current through the coil determines the magnitude of the magnetic field within the coil, and the magnetic field limits the current through the windings because of the restrictions upon superconducting materials, the stored energy in the coil will be a function of the magnetic field strength. The field at the center of the coil, B_o, is[7]

$$B_o = \frac{nI}{2b} \frac{b}{\sqrt{a^2 + .25\ b^2}} \cdot 4\pi \cdot 10^{-7}\ \text{webers/m}^2.$$

The critical current density in the coil is determined not by the field along the coil axis but by the maximum field existing within the coil windings, which, for the assumed rectangular coil geometry, will occur along the inner radius of the coil midway between the ends. The ratio B_{max}/B_o has been determined by IBM computer analysis in Reference 8 for various values of b/a and c/a. For a coil of specific geometry and a given maximum magnetic field, the above equations permit determination of the number of ampere-turns, the inductance, and finally, the energy stored within the coil.

SYSTEMS REQUIREMENTS FOR HIGH ENERGY STORAGE

It was determined by the analysis of Reference 4 that superconducting coils in sizes of many meters in diameter could be capable of storing quantities of energy several orders of magnitude higher than any presently existing energy storage system with the capability of delivering this energy in the form of electric power within a short interval of time.

Since the energy density of chemical propellants using liquid oxygen is of the order of 6×10^9 joules/m^3, this figure is chosen as a design goal for the magnetic coil. To establish the design, a maximum magnetic field within the coil must first be chosen so that the maximum permissible current in the superconducting wire can be determined. The maximum field is chosen to be 12.5 Wb/m^2, corresponding to a current per conductor of 13 amperes, according to Figure 1. By basing the design upon the above given energy density in the coil material, it was determined that a total energy of 1.08×10^{12} joules could be stored in a coil of average radius 17.82 m, length 17.82 m, and winding thickness 0.089 m. The weight of the coil windings would be 1.11×10^6 kg. At the location of the peak magnetic field of 12.5 wb/m^2, a magnetic pressure of 62.25×10^6 newtons/m^2 (9040 psi) would be generated, and a thick, pressure bearing shell would be required to supply the necessary strength to the coil. By using the alloy Ti-6Al-4V in the shell with an average thickness of 0.75 m, the shell weight alone contributes 6.7×10^6 kg to the weight of the device. This alloy was chosen for its high strength, low density, and suitability for cryogenic temperatures.

The coil, shell, and switching mechanism would be enclosed in a double-walled container constructed of sheet titanium alloy with a 10-cm thick, evacuated layer of NRC-2[9] superinsulation, which has a

conductivity of 0.3 microwatts/cm-^{o}K. Assuming the temperature of the external environment to be 300^{o}K, the total heat flux from the external surface of the casing through the insulator to the liquid helium would be 400 watts. A helium refrigerator of 300 kw input would be required to absorb this heat.[10] The refrigerator might weigh as much as 15,000 kg.

If a charging time of 1000 hours were permissible, a 300 kw power plant would be required for this purpose. Considering a SNAP 50 type system, the power plant weight for the combined charging and refrigeration requirements might be 10,000 kg.

Summing the component weights gives a total system weight of over 7,800,000 kg. It is expected that be proper choice of maximum magnetic field within the coil, that is, at some value below 12.5 wb/m^2, a minimum system weight will be found corresponding to a lower shell and a higher coil weight.

SYSTEM COST

In consideration of the cost of the pulse power system, the largest item is the cost of the Nb_3Sn wire. The two million kilometers required for the coil could be obtained for $200,000,000 provided mass production techniques could reduce the price of the wire to 10% of its present cost. The cost of the titanium alloy shell may be of the order of $35,000,000. The cryogenic facility may cost around $2,000,000. Aside from the two 300 kw power plants, which could be nuclear reactors, it is estimated that the system cost will range between $250,000,000 and $300,000,000.

TECHNICAL PROBLEMS

It has been stated that superconducting coils cannot presently be used as rapid discharge devices because of the heat produced by eddy currents set up in the material.[2] For a device of the type described in this paper, for which the magnetic field change per pulse of output energy is very small compared to the maximum field existing within the coil, it is anticipated that the very high heat conductivity of these materials at liquid helium temperatures will permit a rapid enough dissipation of heat from the windings into the liquid helium to prevent loss of superconductivity.[2] Smaller scale experiments to investigate such design problems would be advisable. Safety circuits would be required, as in present large solenoids, to prevent destruction of the coil due to accidental loss of superconductivity while in the energized condition.

The superconducting switch capable of carrying very high currents would require some development effort, as would a means of adequately supporting the coil and its insulating container without providing large heat leakage paths which could necessitate a considerably larger cryogenic facility.

Another design problem which is basic to the concept of obtaining many pulses of energy from a single coil configuration is the physical location of each individual winding so that its magnetic coupling factor with respect to any other winding is a constant somewhat below 1.0.

SUMMARY

It appears that the inductive storage of energy on a sufficient scale to provide a capacity of 10^{12} joules or more is technically feasible as an advanced state-of-the-art concept, but it will require a considerable development effort because of the large scale structures and energy flow rates involved. Once put into operation, the facility will remain in ready condition as long as the liquid helium supply is adequate. The system will deliver short, exponential-like pulses of power upon command, of a magnitude predetermined by system design and at any desired rate. The total energy per unit mass of the $250,000,000 to $300,000,000 system is estimated to be 1.38×10^5 joules/kg, which is believed to be considerably higher than for any other method of electrical energy storage.

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MAGNETIC ENERGY STORAGE USING SUPERCONDUCTING COILS

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The recent discovery of superconducting materials that carry high current densities in magnetic fields approaching several hundred thousand gauss has opened up the possibility of using superconducting inductors to store electrical energy. The advantage of superconducting inductive energy storage is that once the inductor is energized, and a closed superconducting circuit established, then, since superconductors have zero resistance under d.c. conditions, the electrical energy could be stored indefinitely provided the low temperature environment is maintained since no resistance is present to dissipate the stored energy.

The energy storage per unit volume is equal to

$$\text{Energy/volume} = \frac{B^2}{2\mu_o}$$

where B is the magnetic field strength. Figure 1 shows the energy stored per unit volume as a function of magnetic field.

Since the energy density increases as the square of the magnetic field strength, it is clear then that for a compact system we would like to store the magnetic energy at as high a magnetic field as possible.

I. SUPERCONDUCTING MATERIALS

The high field strength superconducting materials available today fall into two main categories - the alloys, and the compounds. The alloys, such as Nb-Zr, Nb-Ti, Ti-Ta and V-Ti[1] are ductile and easy to handle, while the compounds such as Nb_3Sn and V_3Ga are brittle.

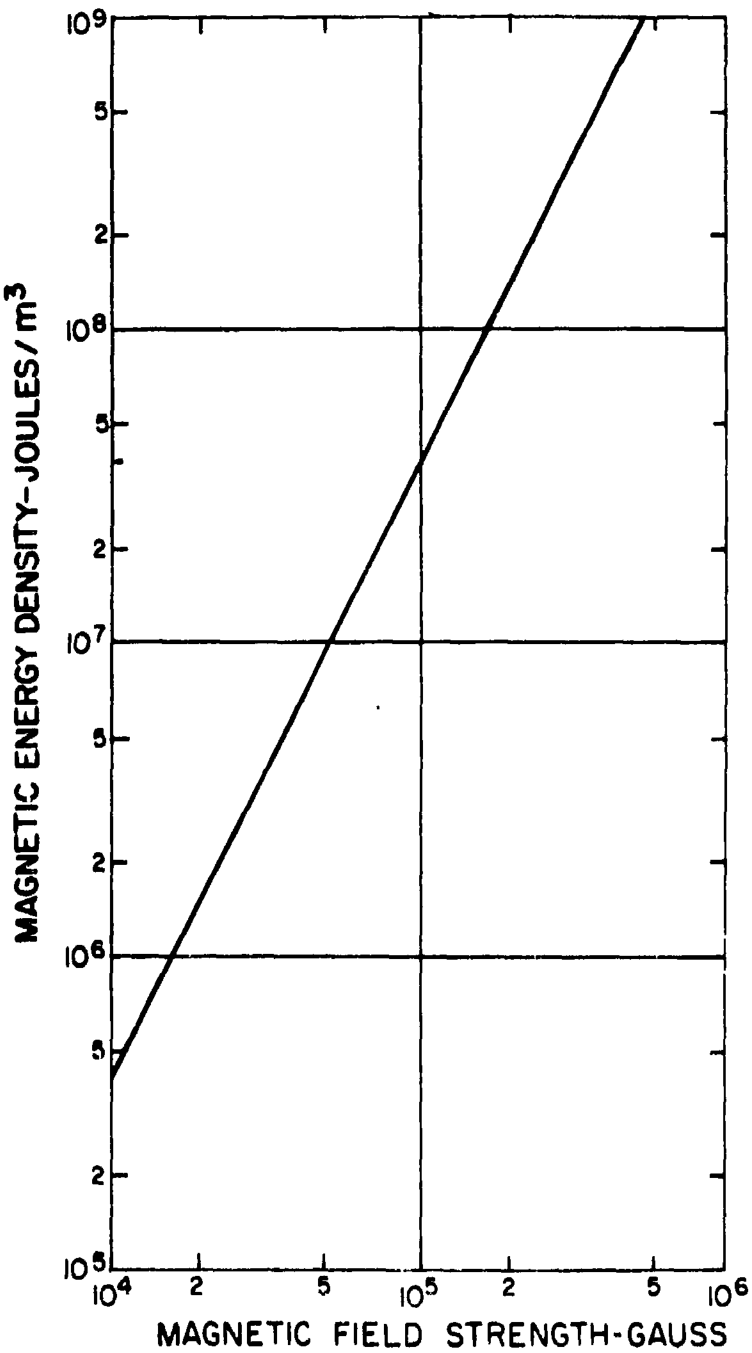

Fig. 1. Magnetic energy density as a function of magnetic field strength

Typical short sample tests at 4.2°K of current carrying capacity versus applied magnetic field for several compositions of the Nb-Zr system are shown in Figure 2. When using Nb-Zr, it is found in general that when wound into a coil the currents that can be passed through the coil are less than that measured in a short sample. Although this phenomenon is not yet fully understood,[2] it is hoped that with further research into the behavior of superconductors the current carrying capacity of coils will approach that of short samples.

The compounds are brittle, and are used either encased[3] or on a substrate.[4] The advantage of the compounds is that they have higher critical fields and higher current carrying capability, based on the cross-sectional area of the superconductor only, than do the alloys.

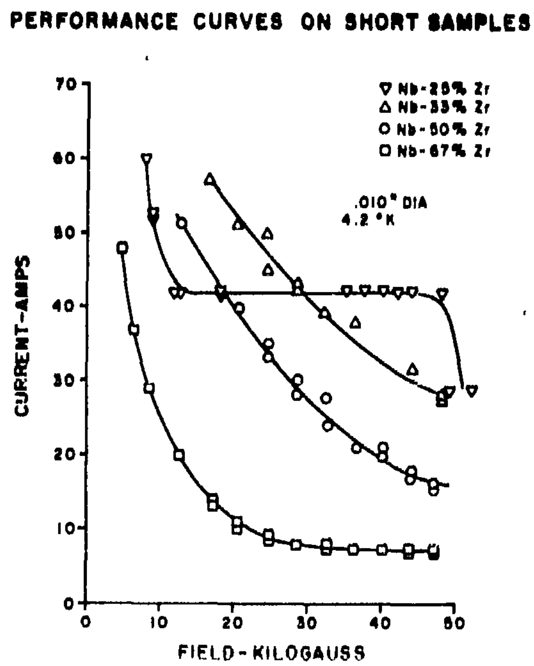

Fig. 2. The above figure shows typical short sample tests of niobium-zirconium wires with varying amounts of zirconium

Short samples of Nb-Ti have shown that it remains superconducting in fields up to about 140,000 gauss,[1] while short samples of Nb_3Sn have been estimated to remain superconducting in fields exceeding 200,000 gauss,[5] and estimated values for the critical field of V_3G_a range up to 500,000 gauss.[6]

The current carrying capacity of commercially available superconducting alloys in short samples today approach 100,000 a/cm^2 (corresponding to 50 amperes in a .010" diameter wire) at 50,000 gauss.

It is expected that superconducting materials will become available commercially which will have higher current carrying capacity as well as higher critical fields.

II. SUPERCONDUCTING INDUCTIVE ENERGY STORAGE

A system using superconductors for magnetic energy storage consists of the superconducting material to generate the magnetic field, the structural material necessary to hold the superconducting material together against the magnetic forces, a system for maintaining the superconductor at low temperature, and a system for charging and discharging. This paper will consider only the superconducting material, the structure necessary to hold it together, and the dewar or container to maintain the environment.

A. Magnetic Configuration

The magnetic field configuration should be such as to result in a maximum energy storage per unit mass of system weight or cost. In addition, the required conductor configuration should be a simple shape so as to make it easy to build. Further, if fast discharges are required, then it becomes undesirable for the magnetic field to link any closed metal loops other than those necessary for the electrical operation of the system, since during fast transients energy would be dissipated in these closed loops.

A configuration which satisfies most of the above requirements is a toroid. The magnetic field is completely contained within the toroid, and no stray fields are present external to it to induce eddy currents, or to interfere with the operation of other electrical apparatus which may be in the vicinity.

Although the choice of a toroid may not be the optimum choice for the magnetic field configuration, it will be used in this paper to obtain results which should be typical and which can be derived relatively easily for any other magnetic field configuration.

The inductance of a toroid using only a single turn is given by:[7]

$$L = \mu_o r \left[1 - \sqrt{1 - (a/r)^2} \right]$$

where r is the major radius, and a is the radius of the circular conductor cross-section as shown in Figure 3. The maximum field which exists at the innermost conductors is:

$$B_M = \frac{\mu_o I}{2\pi (r - a)}$$

where I is the total number of ampere turns.

The total magnetic energy stored is then

$$E = \frac{1}{2} LI^2 = \frac{2\pi^2}{\mu_o} B^2{}_M r^3 (1 - \frac{a}{r})^2 \left[1 - \sqrt{1 - (\frac{a}{r})^2} \right]$$

For a constant maximum magnetic field the maximum energy stored for a given size r occurs if a/r = 1/3, which results in:

$$E = \frac{4\pi^2}{81} \frac{B^2{}_M r^3}{\mu_o}$$

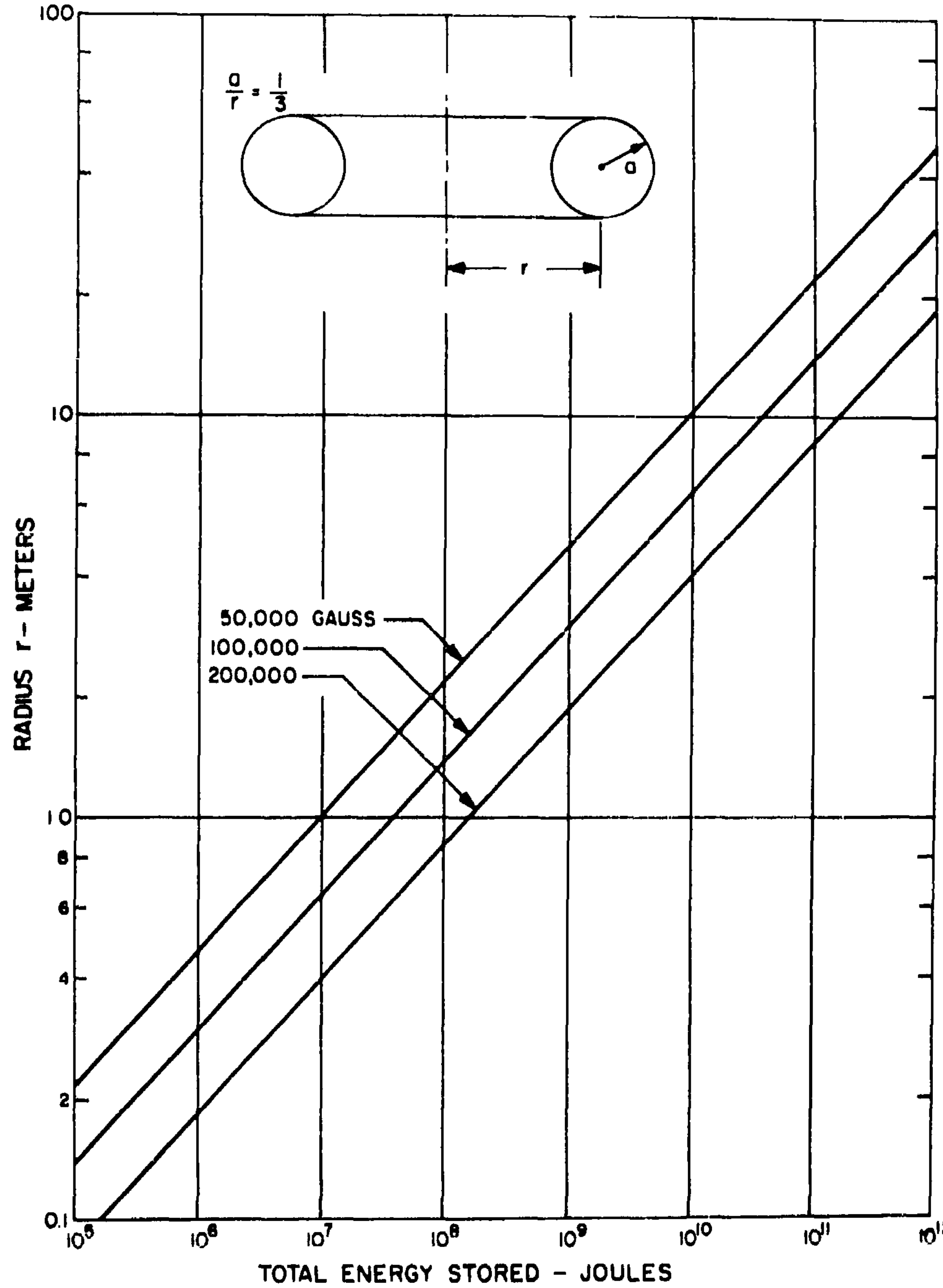

Fig. 3. Size of a toroid as a function of the magnetic energy stored for various maximum field strengths

The size r versus the total magnetic energy stored is shown in Figure 3 for various values of allowable maximum magnetic field.

The amount of superconductor required is readily calculated:

$$M_{sc} = \gamma_{sc} \cdot 2\pi a \frac{I}{j} = \gamma_{sc}\, 4\pi^2\, r^2\, \frac{a}{r} (I - \frac{a}{r}) \frac{B_M}{\mu_o j}$$

where γ_{sc} is the density of the superconducting material, and j is its current density. For the ratio of $a/r = 1/3$, the above formula reduces to:

$$M_{sc} = \frac{8\ \pi^2}{9} \gamma_{sc}\, r^2 \frac{B_M}{\mu_o j}$$

If we take a current density of 100,000 a/cm^2, and 30,000 a/cm^2 and a density of 8.4 g/cm^3 (corresponding to Nb-25% Zr), then the total superconductor mass required is shown plotted in Figure 4 for maximum magnetic fields of 50,000, 100,000, and 200,000 gauss.

B. Dewar

The surface area of the toroid can be obtained as a function of the radius r, for the optimum ratio $a/r = 1/3$:

$$A_{SURF} = 2\ \pi a \cdot 2\ \pi r = 4\pi^2\, r^2 \frac{a}{r} = \frac{4}{3} \pi^2\, r^2$$

The surface area is shown plotted in Figure 5 as a function of stored magnetic energy.

C. Structure

One of the most important considerations in the design of large magnetic energy storage units is that the coils be structurally sound.

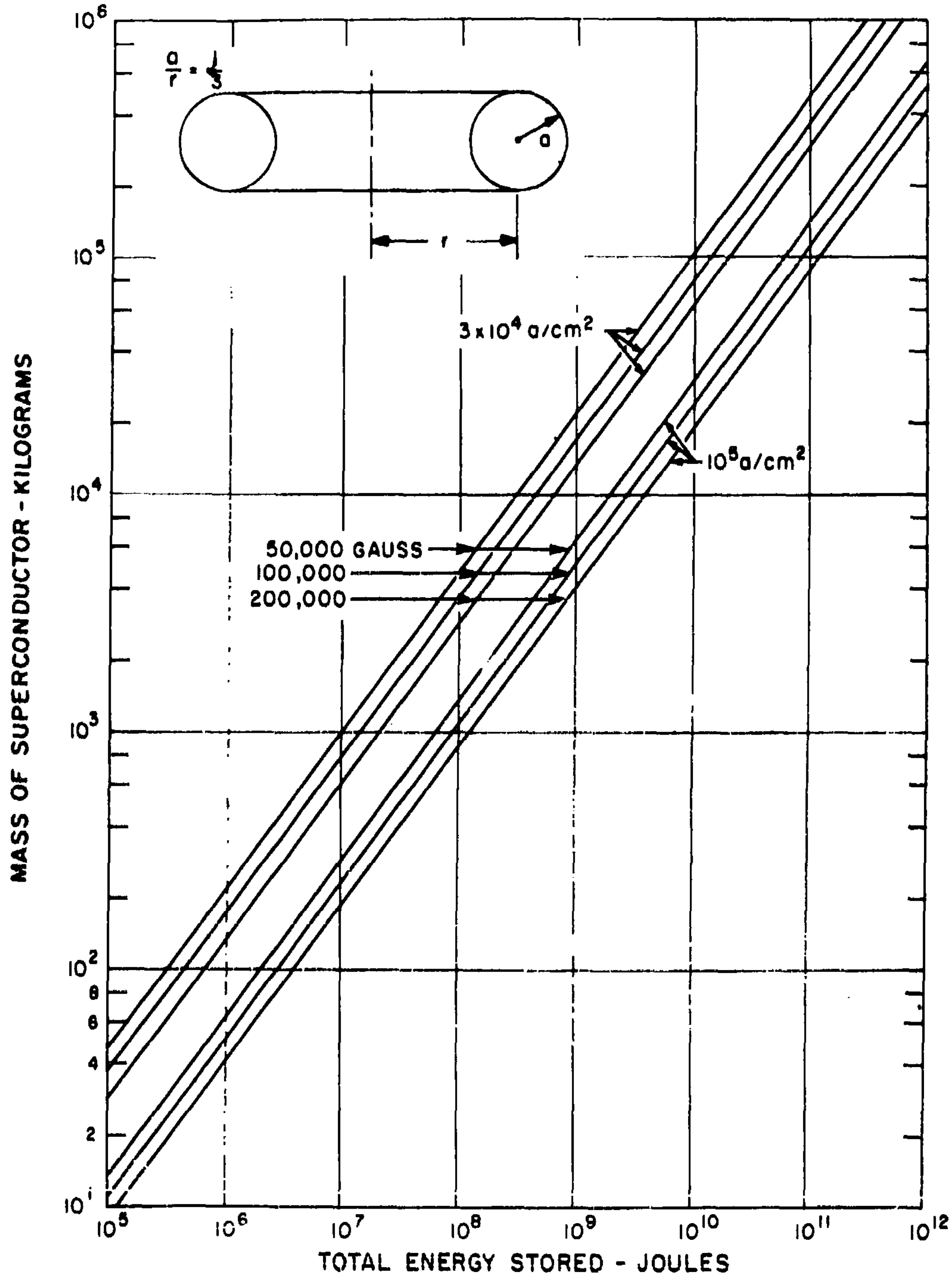

Fig. 4. Mass of superconducting material required as a function of total magnetic energy stored for various magnetic fields and superconductor current densities

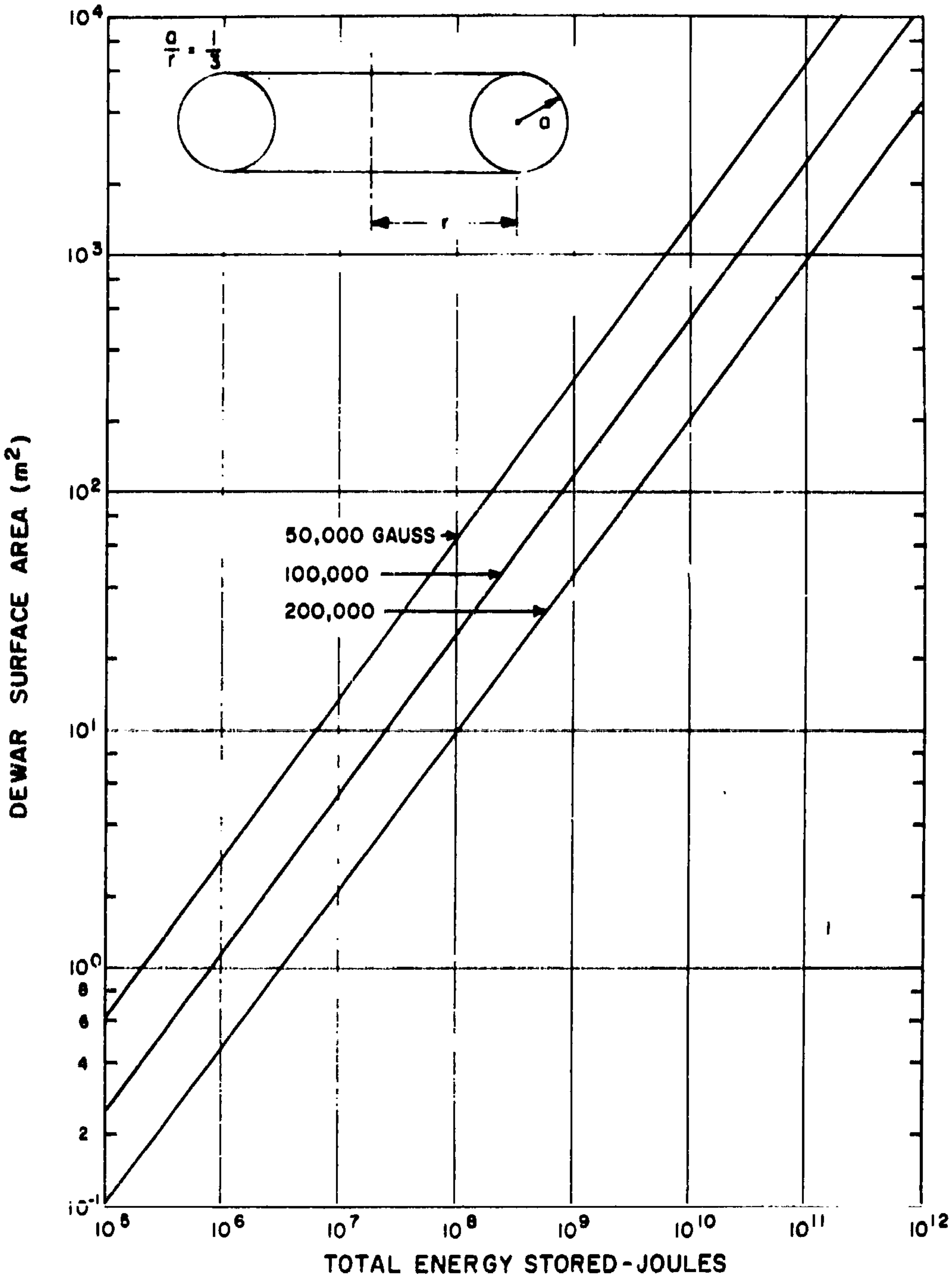

Fig. 5. Surface area of the dewar for a toroidal superconducting coil as a function of the magnetic energy stored, and the magnetic field strength

It has been shown by Levy[8] that a minimum possible structural weight results if all the structure is in tension. Under these conditions Levy shows that the minimum possible structural mass required is:

$$M_{ST} \geq \frac{\gamma_{ST}}{\sigma_W} E$$

where γ_{ST} is the density of the structure, σ_W the working stress, and E the total magnetic energy stored.

In an actual configuration the above minimum structural weight is usually not achieved.

If we assume that the strength to weight ratio of the structural material used is equal about to that of Titanium stressed to 230,000 psi,* then substitution into the above formula results in a minimum possible structural weight of 2.9×10^{-6} kg/joule of magnetic energy stored. This means that until the energy stored becomes of the order of 10 to 100 megajoules, the structural weight is small.

In actual practice for energy storages less than those mentioned above the superconducting material can probably support itself with very little additional structural requirements. However, in the large energy storage region the structure becomes the most massive element. It is interesting to compare estimates of the structural requirements for the toroid with the minimum possible values.

The total hoop force in a direction which is tangent to the circle of radius r is:

$$F_r = -\frac{I^2}{4\pi} \frac{\partial L}{\partial r}$$

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* For fast discharge closed metal circuits formed by metal structure are undesirable since they dissipate energy, so that either a non-metallic structure must be used, or an insulated break in the metallic structure must be provided.

Substituting for I, taking the derivative of the inductance L with respect to r, and substituting $a/r = 1/3$ results in:

$$F_r \approx +.078\, r^2 \frac{B_M^2}{\mu_o}$$

The positive sign denotes compression in the structure.

The total hoop force in a direction which is tangent to the circle of radius a is:

$$F_a = -\frac{I^2}{4\pi} \frac{\partial L}{\partial a}$$

which results in:

$$F_a \approx -0.49\, r^2 \frac{B_M^2}{\mu_o}$$

for $a/r = 1/3$, and is a tensile force.

If the structure is being used to simultaneously support both loads, then the force picture as well as the stresses in a single element of the structure are shown in Figure 6.

If we assume the structure fails by the maximum shear stress theory, then since the stresses in the a, and r direction are of opposite sign, then:

$$\left|\sigma_a\right| + \left|\sigma_r\right| = \sigma_w$$

where σ_w is the working stress in pure tension.

Using this criterion then, for a toroid of $a/r = 1/3$:

$$.077 \frac{r}{t} \frac{\bar{B}_M^2}{\mu_o} + .037 \frac{r}{t} \frac{\bar{B}_M^2}{\mu_o} = \sigma_w$$

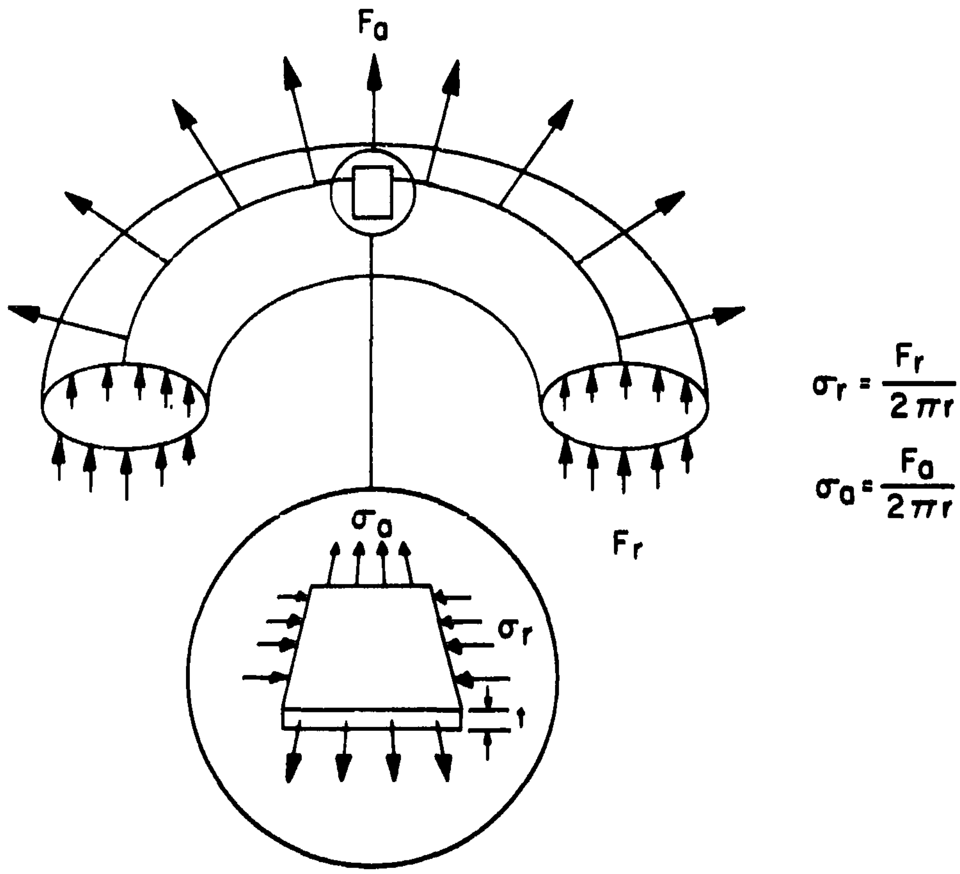

Fig. 6. Force, and stress picture for a toroidal inductor. The force F_a is a tensile one, F_r a compressive one. An element of the structure sees compression in one direction and tension in the other

where t is the thickness of the structure uniformly distributed over the surface of the toroid. If we multiply the thickness of the structure by the surface area and by the structural density γ_{ST} the total structural mass is:

$$M_{ST} \approx 1.50 \; \frac{\gamma_{ST}}{\sigma_W} \; \frac{r^3 B_M{}^2}{\mu_o}$$

If we divide by the energy stored, then:

$$\frac{M_{ST}}{E} \approx 3.1 \frac{\gamma_{ST}}{\sigma_w}$$

So we can see that the actual structure in this case is about 3 times as heavy as a structure would have to be to contain the same amount of energy with an all tension structure.

Ingenuity in magnetic field configuration and structural design to yield a pure tension structure could greatly cut down in the structural mass requirements.

It has been shown above that the structural mass required is proportional to the magnetic energy stored, so that for a large enough system the structure becomes the most massive element. While for small energy storage the superconductor itself can be used as the structure, and hold the coil together, at the higher energy storages, the separation of the structural and electrical functions results in a less expensive as well as a less massive system.

D. System Weights and Costs

After having calculated the required mass of superconductor, the required mass of structure, and the surface area of the dewar, we need only assign a surface density to the dewar to estimate the system weight. Airborne dewars today have surface densities of about 1 - 1.4 lbs/ft^2.[9] Using the lower value, the system weight in kilogauss per megajoule of energy versus the total energy stored is plotted in Figure 7 for superconducting material able to carry 10^5 a/cm^2, as well as for material which carries only 3×10^4 a/cm^2, a value which is being obtained in laboratory coils today (it should be noted that no allowance has been made for weight of protective circuitry of any kind).

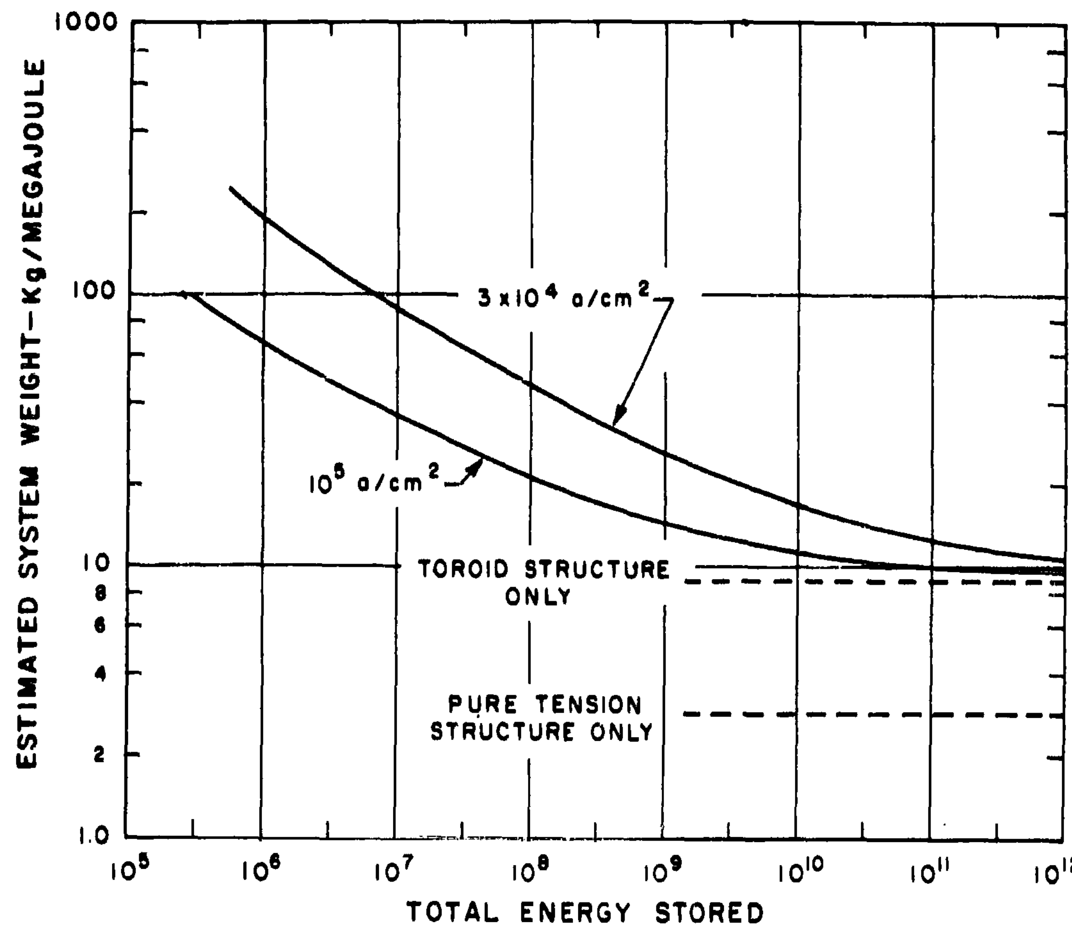

Fig. 7. The estimated weight per unit energy, stored for superconducting material at 3×10^4 a/cm^2 and 10^5 a/cm^2. It can be seen from the figure that as the energy increases the system weight approaches that of the structure above. The pure tension structure limit is the minimum possible structural weight for a structure with a strength to weight ratio equal to that of titanium. (The dewar and superconductor mass are estimated for energy stored at 100,000 gauss).

The system costs can be estimated by assigning a cost per unit mass of the superconducting material, a cost per unit mass of the structural material, and a cost per unit area of the dewar surface.

Superconductors available today cost in the neighborhood of \$400/lb. In very large quantities, the superconductor cost could decrease to about the cost of the raw materials, or about \$50/lb.

The cost of structural material can vary considerably depending on the material used. But let us take as an initial estimate a structural cost equal to the cost of titanium at \$5/lb.

The cost of surface area of dewars can again vary considerably, again, let us take \$100/ft^2 as the cost per unit surface area.*

The estimated costs per joule of energy stored for superconductor current densities of 3×10^4 a/cm^2 and 10^5 a/cm^2 is shown in Figure 8 for costs of superconducting material ranging from \$400/lb to \$50/lb. It is apparent from Figure 8 that the current density as well as price of the superconductor are the main factor in determining the cost per joule of energy stored. The top curve corresponding to 3×10^4 a/cm^2 and \$400/lb of material corresponds to the present state of affairs. The lower curve at 10^5 a/cm^2 and \$50/lb corresponds to an optimistic (but realistic) estimate of what could be achieved in the future. Since the time to build large systems is considerable, a curve of cost vs energy storage reflecting improvements in technology should start from the upper curve at low energy storages and fall to the lower curve at high energy storages.

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* This cost is estimated from three metal dewars purchased. The smallest being 4" ID and 4 ft high, the second being 14" ID and 6 ft high, the third being 24" ID and 6 ft high.

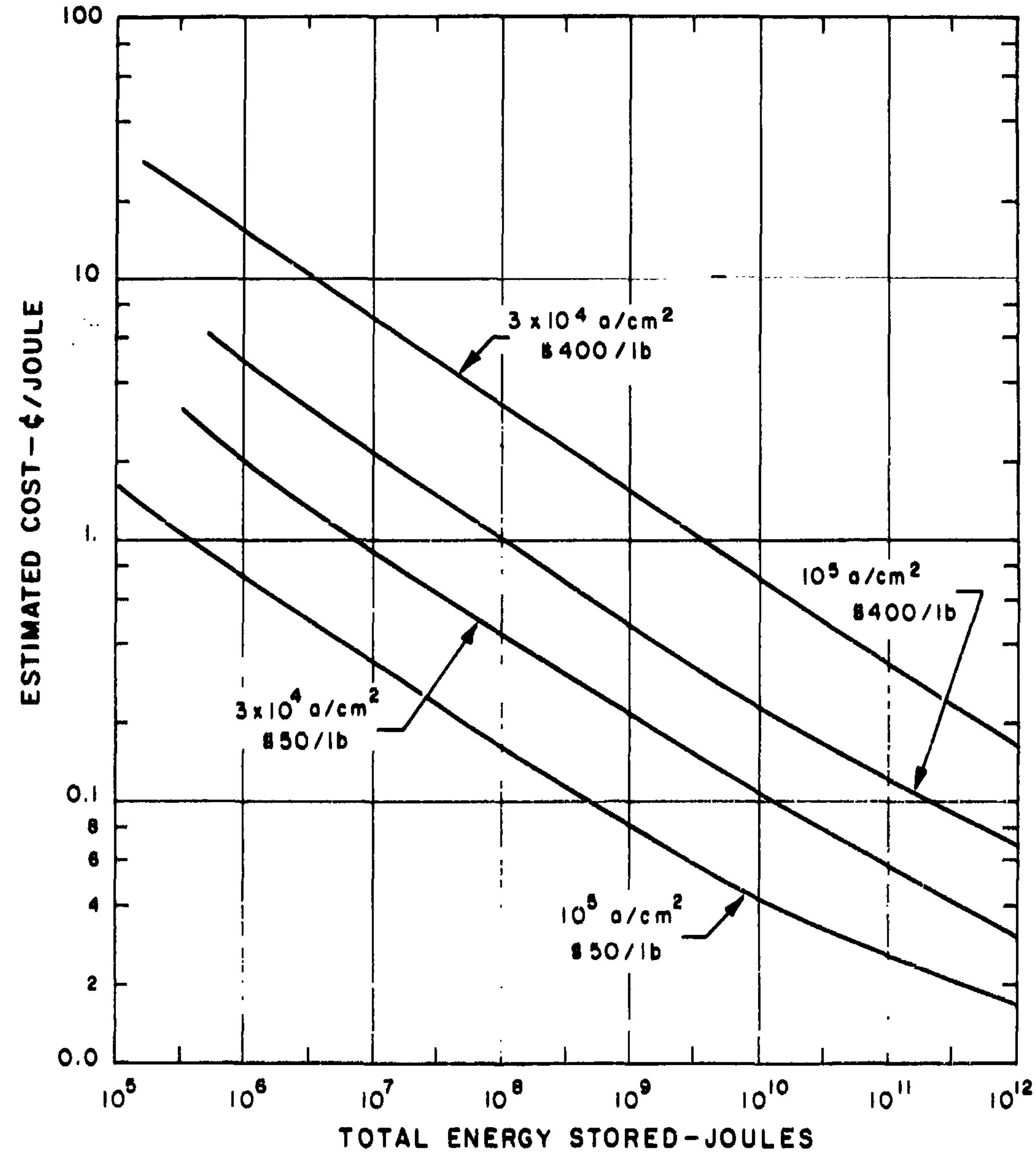

Fig. 8. Estimated system cost per joule of energy stored for current densities of 3×10^4 a/cm^2 and 10^5 a/cm^2 and for superconducting material costs of \$400/lb and \$50/lb. The structural cost is taken as \$5/lb and the dewar cost as \$100/ft^2 of dewar surface area. (The dewar surface area and superconductor mass are estimated for energy stored at 100,000 gauss).

E. Energy Removal

An inductor is an element which tends to keep a constant current flowing through it. This means that if it is suddenly put across a load the current through the load will be that which was flowing initially through the inductor.

Fast discharge of an inductive element requires a large product of the voltage and current. Since the maximum voltage which can be easily handled is limited, it is necessary to discharge the inductor at high currents. This can be done by charging the inductor at a very low voltage and high current. However, this requires large bus bars and is probably impractical for superconductors.

If charging is to be done at moderate or low currents, then the energy may be removed by a secondary coupled circuit which is connected to the load, or by charging the coil up in series, then switching many sections so that they discharge in parallel across a single load.

In the coupled circuit scheme the primary inductive circuit must be opened rapidly compared with the discharge time of the secondary circuit through the load, for efficient transfer of energy from the primary to the secondary circuit. This scheme still suffers from the fact that even though a load can be supplied at a reasonable voltage and high current, the load voltage reflected into the secondary circuit is still very high.

From the point of view of charging at small currents and discharging at high currents, switching of several coil sections from series (for charging) to parallel (for fast discharge) probably is the most promising approach when viewed in terms of today's fine wire superconductors.

One problem which should be pointed out is the fact that superconductors such as Nb-25% Zr do exhibit considerable resistance under transient conditions, and the heating which may result in a fast discharge may drive the whole coil normal.

If the coil is directly connected across the load, this means that the energy would be dissipated internally and not supplied to the load.

III. STATE OF THE ART IN SUPERCONDUCTING COILS

Superconducting coils today are made mainly for the purpose of providing high magnetic fields for laboratory experiments.

All of the coils which are commercially available today are made with Nb-Zr wire and go to fields approaching 60,000 gauss.

The main problems at the present in the superconducting magnet field are:

1. Use of very fine wires.
2. When run in a coil, the current carrying capacity is less than in short samples.
3. Provision of protecting circuity.
4. Materials.

It has been found that fine wires are necessary for high current densities, and consequently .010" diameter wire is used for the large majority of magnets being wound today. This higher current carrying capacity is normally associated with the amount of cold work in the material. It is essential to gain a basic understanding of the current paths in superconducting materials, and how they are affected, so that current carrying capacity in conductors of different sizes and shapes can accurately be predicted.

The second problem is one of not fully understanding all the pertinent superconducting phenomena, or maybe that the wire itself is non-uniform so that coil behavior is characterized by the "weakest link in the chain." At the present one can only guess at the current carrying capacity of a coil which is radically different in size or shape from ones already built. Mechanisms have been suggested for this behavior,[2] however, further work is necessary before this effect is understood.

The coils being built today all have protective circuitry to prevent damage to the windings in case of accidental or intentional transition in the normal state. This protective circuitry becomes more involved the higher the coil energy. Its net effect, however, is to slow down any transients, and consequently start-up and shut-down are slow. For coils to be used for fast discharge of energy this protective circuitry must be either disconnected prior to discharge or left out entirely.

A considerable amount of effort is needed to fully understand the behavior of superconducting materials and to develop practical superconductors with critical fields over 100,000 gauss and with high current carrying capabilities.

The most magnetic energy that has been stored in a superconducting coil system has been in a 5" ID solenoidal system, one spool of which is shown in Figure 9. A set of three of these spools shown in Figure 10 has been energized to 34,000 gauss with a total magnetic energy of 45,000 joules.

Larger coils are now being constructed with energy storages in the several hundred thousand joule range.

IV. CONCLUSIONS

The use of superconducting inductive energy storage has considerable promise when viewed in terms of size, weight and cost. However, at the present several problems exist which must be investigated to make this type of energy storage practical. These areas are:

1. Basic properties of superconducting materials both under a.c. and d.c. conditions.
2. Development of superconductors with higher current carrying capacities and higher critical fields.
3. Development of methods for fast removal of the stored energy, taking into account transient properties of superconductors.

4. For large systems the main weight is structural so that magnetic configurations which could be supported by purely tension structures should be investigated.

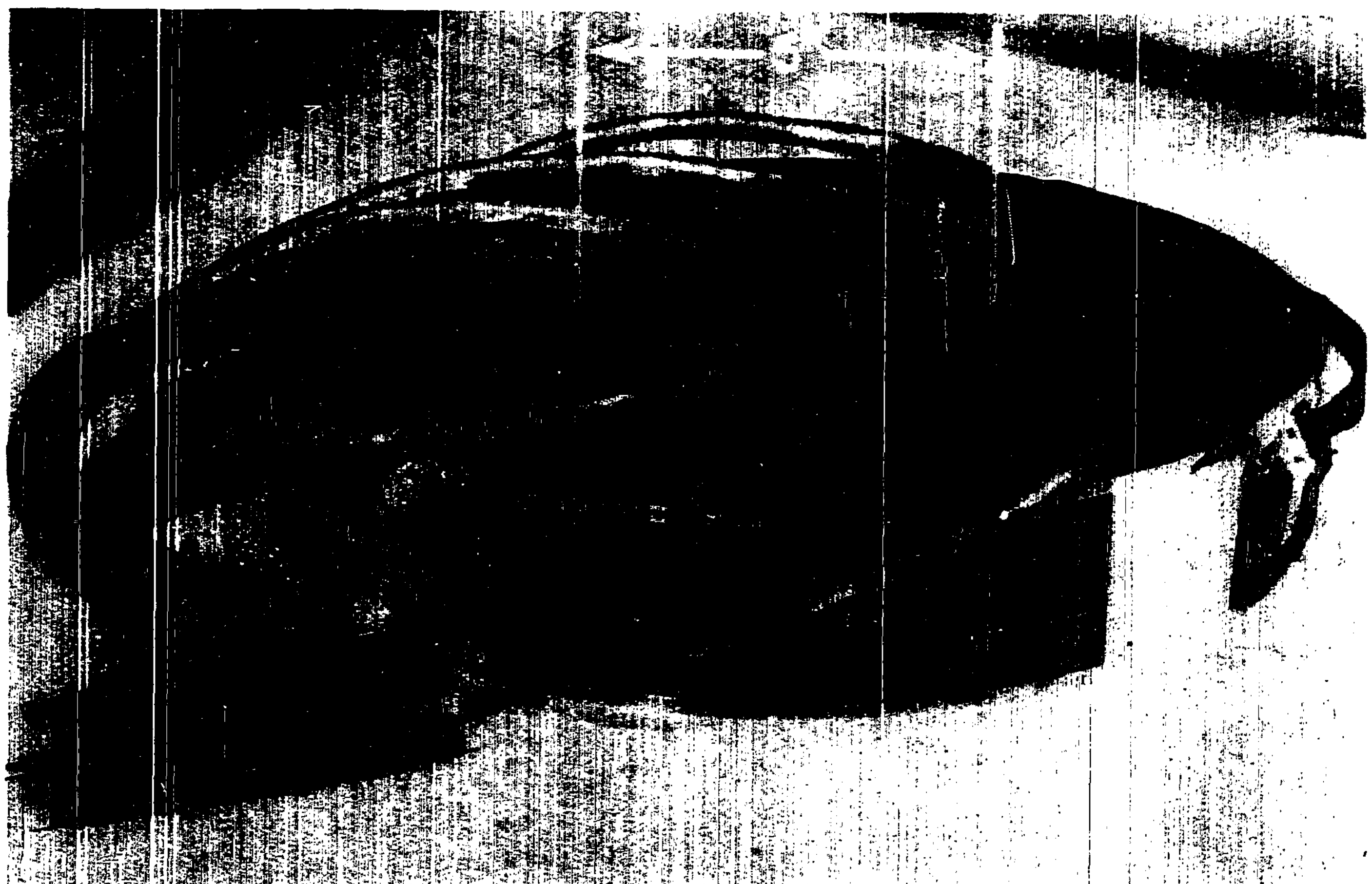

Fig. 9. Avco's SC-502 superconducting coil. This coil produces fields up to 15,000 gauss at the center, and has an inductance of about 100 h.

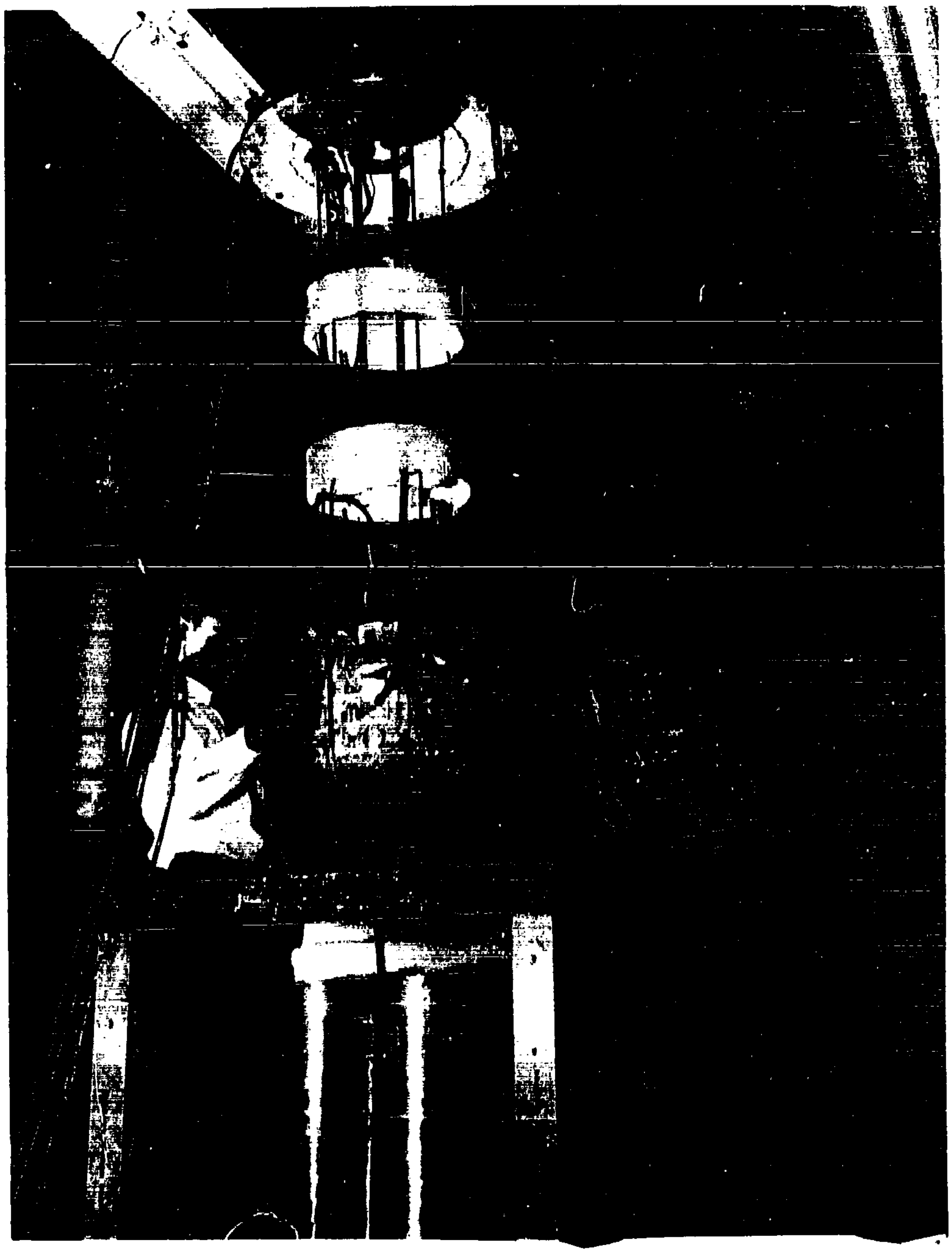

Fig. 10. A set of three SC-500 coils being withdrawn from Avco's 14-inch diameter superconducting magnet test stand. This set of coils has produced fields of 34,000 gauss in an internal diameter of 5 inches. Under these conditions the magnetic energy stored was 45,000 joules.

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NOTE ON SUPERCONDUCTIVE INDUCTOR ENERGY STORAGE

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Princeton, N. J.

February 18, 1963

This note is addressed to the problem of storing great quantities of electrical energy which can then be delivered to a load in a very short period of time. The observations herein presented must be qualified by noting that we have not carried out a definitive study of this problem. Our perfunctory efforts have, however, disclosed no basic unfeasibility in the use of superconductive inductors for this purpose. The several thoughts expressed here are simply put forth to provide insight and perspective for a more complete study.

1. RCA has developed a method of depositing niobium stanide on various substrates ranging from steel wire to ceramic cylinders and disks. The superconductor material requires no further working after deposition and when the substrate is flexible as in the case of steel wire, the resulting superconductive wire remains flexible and can be bent around reasonable curves without detriment to its electrical characteristics. The properties of the superconductors that result are discussed in some detail in the attached appendix, and for purposes of present considerations, we will simply note that electric current densities possible in this superconductive material are in excess of 10^5 amperes per square centimeter in magnetic fields in excess of 150,000 gauss.

2. The density of energy stored in the magnetic field varies as the square of the magnetic induction (B^2) so that there is a significant advantage when storing vast amounts of energy to using the highest possible field. For example, at 150,000 gauss,

the energy density is 10^8 joules per cubic meter so that very large amounts of energy may be stored in a toroid of not spectacular dimensions.

3. The problem of containing the field, however, is not insignificant. For containment purposes, the field behaves like a pressure. The pressure associated with 150,000 gauss is about 900 atmospheres and requires a steel shell about a foot thick to provide the required tensile hoop strength. It is interesting to note, however, that the amount of steel required depends only upon the amount of energy stored, and not upon the strength of the magnetic field. This results since the same energy with lower fields requires a greater volume with lower pressure. This is illustrated with the following simple dimensional argument.

The energy stored varies as the field squared times a basic dimension cubed.

$$E \sim B^2 L^3$$

The wall thickness varies as the pressure times a basic dimension

$$d \sim PL \sim B^2 L$$

The weight of steel varies as the wall thickness and times the basic dimension squared

$$w \sim d L^2$$

Hence

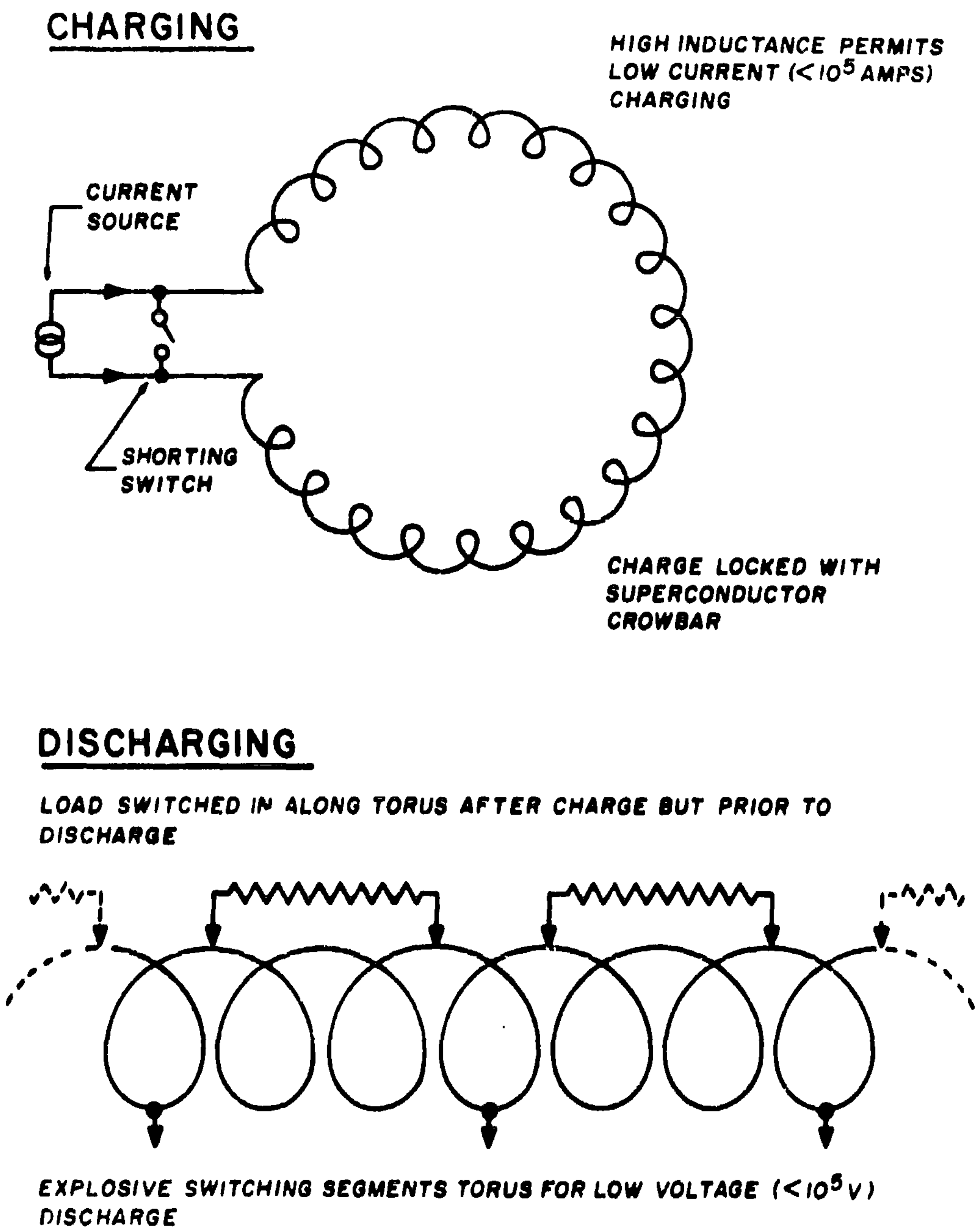
$$E \sim w.$$

Since the structure must support the forces on the inductor, consideration must be given to preventing the structure from itself being a shorted turn. Clamped, mica insulated, slots in a steel structure appear feasible, but low conductance plastic containers should be investigated.

4. Tori are interesting as containing geometries because they provide fairly uniform interior fields and very little stray field outside. Individual tori for each pulse would provide the greatest reliability.

5. Charging and discharging requires special consideration. Switching to change the value of the inductance between charge and discharge is necessary to avoid either excessive charging current or excessive discharge voltage. However, configurations exist which permit all switching at no load except for the final discharge which can be done with positive explosive opening switches. The sketch in Figure 1 illustrates such an arrangement.

6. Raw pure niobium costs about $40 a pound, and tin costs $10 a pound. Assuming an operating current density of 10^5 amperes/cm^2, the raw costs for these materials is then $0.0002/joule. Even assuming an unlikely order of magnitude increase in cost for processing and fabrication shows this material to be competitive for the particular use of fast delivery of large amounts of energy.



CHARGING
HIGH INDUCTANCE PERMITS LOW CURRENT (< 10⁵ AMPS) CHARGING
CURRENT SOURCE
SHORTING SWITCH
CHARGE LOCKED WITH SUPERCONDUCTOR CROWBAR
DISCHARGING
LOAD SWITCHED IN ALONG TORUS AFTER CHARGE BUT PRIOR TO DISCHARGE
EXPLOSIVE SWITCHING SEGMENTS TORUS FOR LOW VOLTAGE (< 10⁵ V) DISCHARGE

Fig. 1.

APPENDIX A

RCA Chemically-Deposited Superconducting Niobium-Tin (Nb_3Sn)

by

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The superconductor Nb_3Sn has the most desirable superconducting properties for the construction of solenoids with field strengths greater than 100,000 gauss. The inherent brittleness of Nb_3Sn however seemed to present major obstacles in the design and the construction of high-field, large volume solenoids.

Recently at RCA Laboratories a unique chemical vapor-deposition process was developed which circumvents the problem mechanical properties of this material. In this process a film of Nb_3Sn is deposited in a continuous manner onto a moving metallic ribbon substrate. The resulting coated ribbon is very flexible and strong - the flexibility of the Nb_3Sn film is due to its relative small thickness (by analogy to a thin glass fibre), while the strength is derived from the substrate.

The vapor-deposition process is described in Appendix B which also includes the description of a 10,000 gauss solenoid constructed of Nb_3Sn-coated platinum substrate.

Continuing research and development of the Nb_3Sn vapor-deposition process has been directed to the construction of high field solenoids and to the achievement of commercial production capacity. Among the notable achievements in these areas are the development of high-strength steel ribbon substrates and the introduction of a solenoid design in which individual single ribbon width, multiple-layer discs ("pies") are wound which can be stacked together to form a complete to torus or solenoid of desired size or length (See Figure 1).

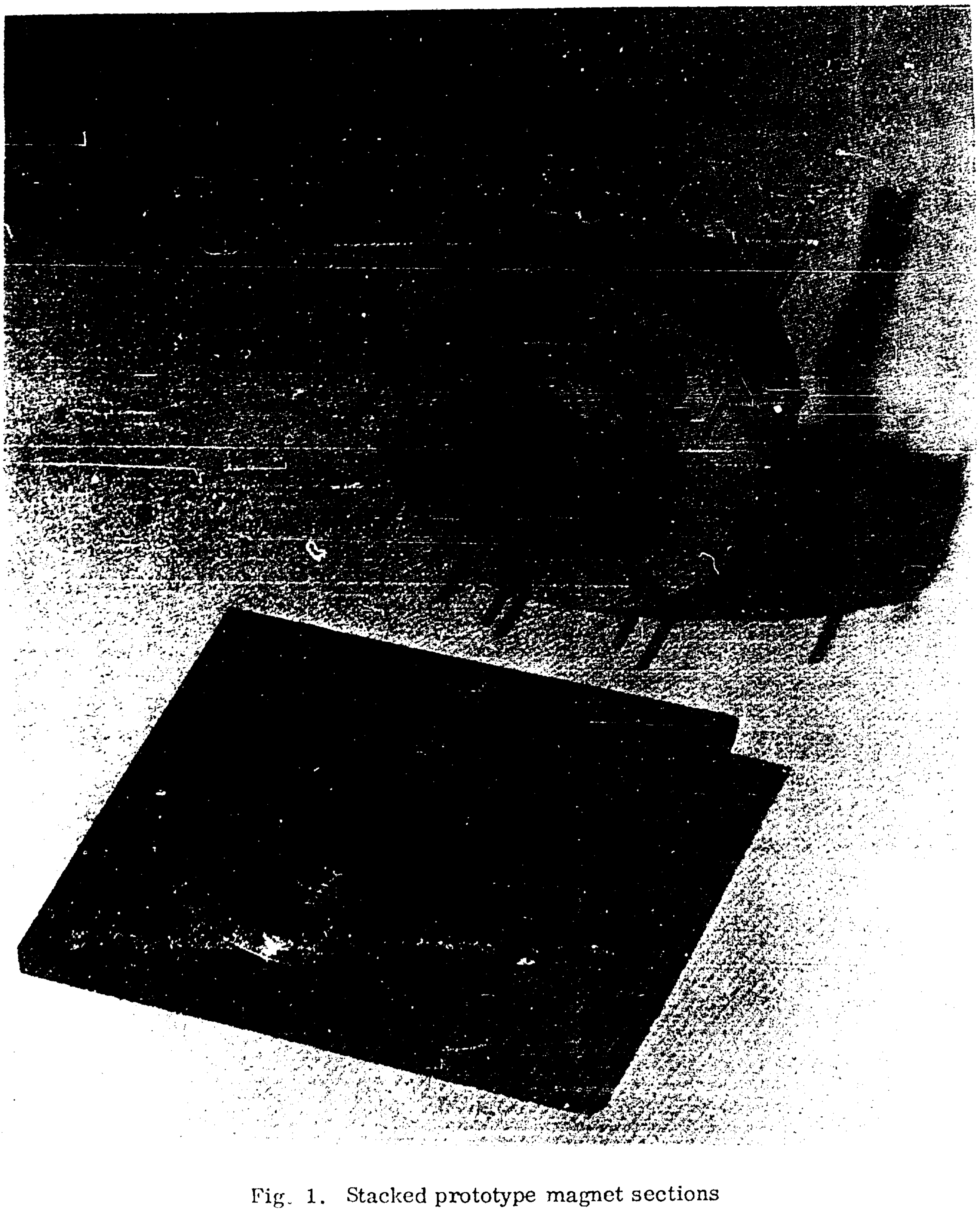
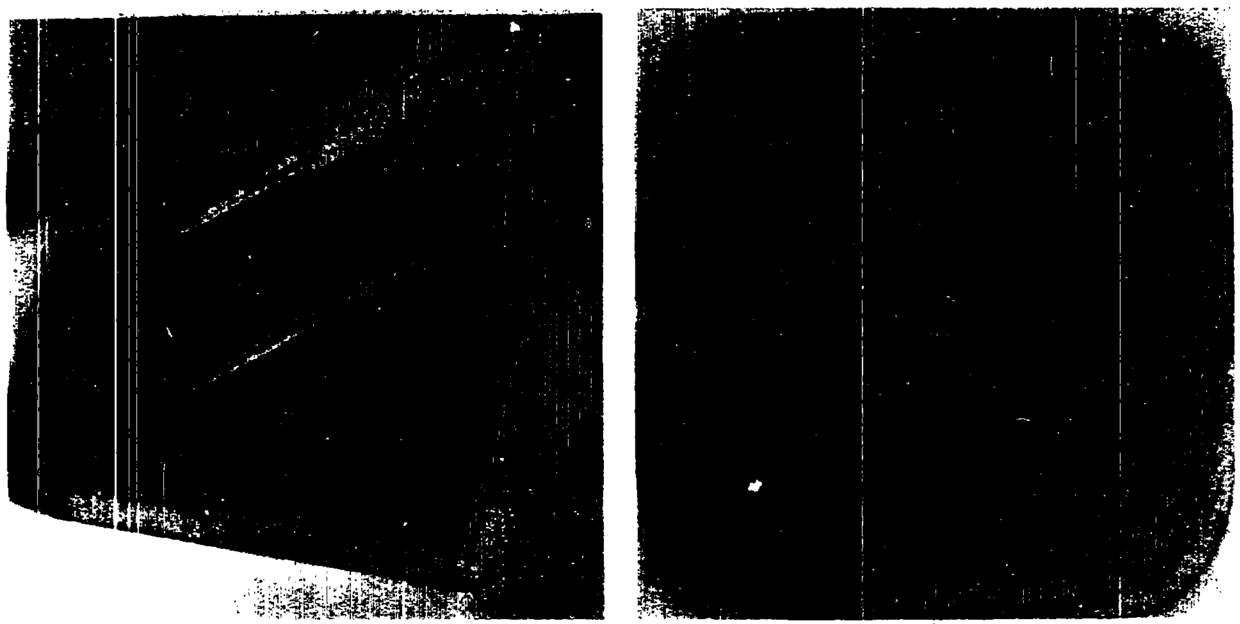


Fig. 1. Stacked prototype magnet sections

At the present time a solenoid measuring approximately 2" I.D. and 5" O.D. consisting of 20 "pies" is under construction and its expected field is 50,000 gauss. The ribbon used in its construction is 0.090" wide and 0.002" thick and has a 0.003"-thick deposit of Nb_3Sn. Pending the evaluation of the performance of this solenoid other designs leading to higher fields and working volumes are contemplated.

The RCA vapor-deposition technique is also suitable for the deposition of Nb_3Sn on large areas of metallic and ceramic substrates having various geometries. Some examples are 1" wide 0.005" thick metallic strips capable of carrying several hundred amperes at high fields, films on ceramic plates with predetermined design (Figure 2) and Nb_3Sn-coated ceramic cylinders (Figure 3) which have been shown useful for flux trapping and magnetic shielding.



(a) (b)

Fig. 2. Nb_3Sn deposits (≈ 5 mil) on ceramics

(a) polished flat
(b) continuous spiral

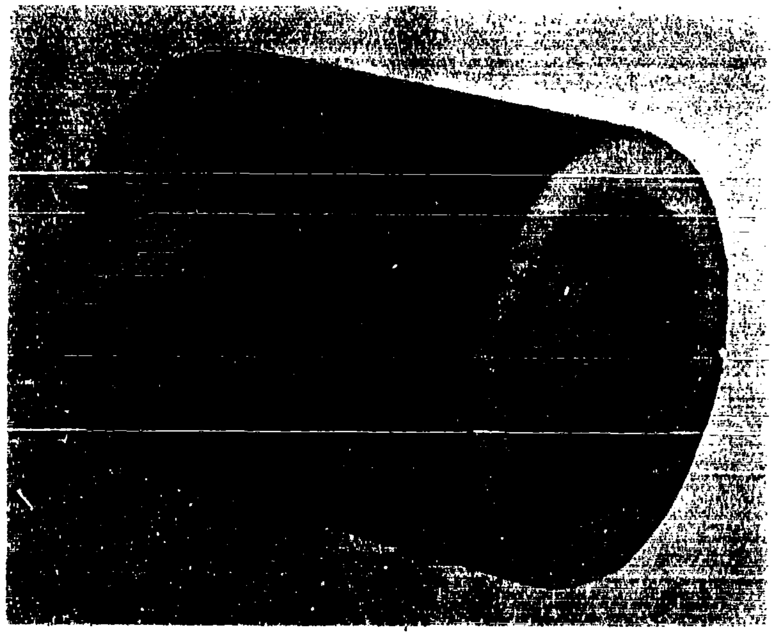


Fig. 3. Nb_3Sn deposit on alumina cylinder (1/2" I.D.)

APPENDIX B

VAPOR DEPOSITION OF Nb_3Sn

by

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ABSTRACT

A vapor-phase transport method of preparation of the superconducting compound Nb_3Sn has been developed, consisting of a simultaneous reduction of gaseous chlorides of niobium and tin on the surface of solid substrates at temperatures ranging from 900 to 1200°C. Lustrous and visibly crystalline films and thick deposits of Nb_3Sn have been prepared with density greater than 99% of the theoretical density. Based on this method, a continuous process of coating wire and ribbon with Nb_3Sn has been developed. The resulting materials are suitable for use in superconducting solenoids as demonstrated by the construction of a 10,360-gauss solenoid. Critical current densities as high as $5x10^5$ amp/cm^2 have been measured for such ribbon in a transverse dc field of 93.5 kilogauss and $1.5x10^5$ amp/cm^2 in a pulsed longitudinal field of 170 kilogauss.

This paper has been presented at the Technical Conference on Advanced Electronic Materials, AIME, Philadelphia, August 1962.

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I. Introduction

The unusual properties of Nb_3Sn, in particular, its high superconducting transition temperature[1], its high critical magnetic field[2] and its capability of carrying large currents at high magnetic fields without power dissipation[3] make it an intriguing material from the standpoint of theory and application. The importance of this material has already been demonstrated by the construction of a 70,000-gauss solenoid by Kunzler[4]. Nevertheless, research and widespread application have been hampered by the brittleness and porosity of the available material which was prepared in the past by metallurgical sintering techniques.[1,3,5,6]

Recently a vapor-phase deposition process has been developed for the preparation of well-defined crystals and films of Nb_3Sn in forms and with mechanical properties suitable for widespread use in both research and application. This paper is concerned with a detailed description of this process and the superconducting properties of the vapor-deposited material.

II. Results and Discussion

A. Crystals and Films of Nb_3Sn

Preparation of Nb_3Sn by gas-phase reactions appeared to be feasible because both niobium and tin metals can be obtained by a reduction of their respective gaseous chlorides at temperatures well below 1000°C[7,8]. Hence, an attempt was made to carry out a simultaneous reduction of a mixture of these chlorides to yield Nb_3Sn directly without the intermediate formation of the free metals.

In initial attempts, two different pairs of chlorides $NbCl_5$- $SnCl_2$ and $NbCl_5$-$SnCl_4$ were used as starting materials. The apparatus had three temperature zones and an open end for a dynamic-flow operation. In each case Nb_3Sn film deposits were formed with crystal structure and T_c identical to the sintered compound. However, in these attempts difficulties were encountered in handling these highly hygroscopic chlorides and in adjusting their partial pressures to appropriate values. The solution to these problems was found in the construction of an apparatus where sintered Nb_3Sn is used as the starting material, which is then directly chlorinated with chlorine gas, and where the resulting mixture of gaseous metal chlorides (mainly $NbCl_5$ and $SnCl_2$) is converted back to Nb_3Sn by introducing hydrogen. This apparatus is schematically shown in Fig. 1. It should be pointed out that although the chlorination and the reduction are carried out at the same temperature, at the chlorination site the temperature is always visibly higher due to the highly exothermic reactions taking place. The rate of flow of the chlorides and to some extent the rate of deposition of Nb_3Sn are controlled by controlling the rate of flow of chlorine gas. The temperature of the furnace can be maintained in the range of 900-1200°C with good results although formation of Nb_3Sn was observed as low as 730°C. It was not possible to go to temperatures much above 1200°C because of the deterioration of the quartz apparatus. The deposition was usually allowed to run from one to three hours during which time up to 15 g of sintered Nb_3Sn was consumed and about 25 to 75 percent of this amount redeposited as Nb_3Sn. The remainder was deposited

as other species usually a black cubic impurity with a = 5.96 Å or passed out of the exhaust as unreacted chlorides. Nb_3Sn deposited in the form of single-phase polycrystals at H (Fig. 1) and as polycrystalline films in tube I; outside of these areas, at J, films containing Nb_3Sn also formed, but they always contained other codeposited species in amounts increasing with the distance away from tube I. These observations indicate that an increase in the ratio of HCl to the metal chlorides is detrimental to the deposition of Nb_3Sn. Examples of vapor-deposited Nb_3Sn are shown in Fig. 2.

B. Wires and Ribbons of Nb_3Sn

The vapor-deposition process of Nb_3Sn was soon recognized to be well suited for coating of refractory metal wires and ribbons for superconducting solenoid applications; however, the process had to be made continuous to be capable of producing great lengths of Nb_3Sn in this form. This requirement implied that during the process the walls of the apparatus had to be kept free from deposition of Nb_3Sn or other condensations which would tend to congest the apparatus. Experience gained with the deposition of Nb_3Sn crystals indicated that the approach to this problem was to maintain the apparatus at a temperature which would be too low for Nb_3Sn to form, but high enough to volatilize the metal chlorides. The deposition of Nb_3Sn on the wire surface would then be accomplished by pulling the wire through the apparatus, and heating it by its own resistance to a temperature necessary for the process to occur.

A schematic diagram of such apparatus appears in Fig. 3. The apparatus consists mainly of resistance furnace and a quartz

deposition chamber designed for a dynamic-flow operation. The gas feed and exhaust are located near the opposite ends of the deposition chamber. The ends of the chamber are fitted with plugs slotted to allow the wire, pulled by a variable speed motor, to pass through the deposition chamber as it is coated with Nb_3Sn. Electrical contacts at the ends of the chamber pass current through the wire to heat it to the desired temperature.

The first attempts to find a suitable temperature at which to maintain the apparatus failed because of the formation of a dark, solid substance, presumably $NbCl_3$, which formed freely below 700°C. This problem was resolved by the application of the following qualitative thermodynamic arguments:

The overall chemical reaction for the vapor deposition of Nb_3Sn can be written as the sum of the three following reactions

$$3\ (NbCl_5 + 2\ 1/2\ H_2 \longrightarrow Nb + 5\ HCl) \qquad (1)$$

$$SnCl_2 + H_2 \longrightarrow Sn + 2HCl \qquad (2)$$

$$3\ Nb + Sn \longrightarrow Nb_3Sn \qquad (3)$$

$$3\ NbCl_5 + SnCl_2 + 8\ 1/2\ H_2 \longrightarrow Nb_3Sn + 17\ HCl \qquad (4)$$

All species in Eq. 4 except Nb_3Sn are gaseous, therefore, the equilibrium constant K_p can be written in terms of the partial pressures p_{gas} of the gases:

$$K_p = \frac{(P_{HCl})^{17}}{(P_{NbCl_5})^3 (P_{SnCl_2})(P_{H_2})^{8.5}} \qquad (5)$$

The values of K_p increases monotonically with temperature. Thus, one control over the deposition is achieved by controlling the temperature. Additional control over the deposition of Nb_3Sn can be attained by varying the amounts of HCl in the gas stream as indicated by the numerator in Eq. 5, which suggests that the forward reaction (Eq. 4) can be retarded by the addition of gaseous HCl into the gas feed.

A similar situation was encountered with the formation of $NbCl_3$ which takes place according to the reaction[7]

$$NbCl_5 + H_2 \longrightarrow NbCl_3 + 2\ HCl \qquad (6)$$

for which the equilibrium constant is

$$K_p = \frac{(P_{HCl})^2}{(P_{NbCl_5})} \ . \qquad (7)$$

Eq. 7 indicates that the forward reaction can also be retarded by the addition of HCl. It was indeed found that in the range of 720-740°C controlled addition of HCl into the gas feed completely prevented the formation of $NbCl_3$, and drastically reduced the already slow deposition of Nb_3Sn on the walls of the apparatus. This allowed for continuous operation of up to 50 hours. The presence of controlled excess of HCl did not prevent the deposition of Nb_3Sn on the wire surface at approximately 1000-1200°C, since the value of the equilibrium constant (Eq. 5) is sufficiently high at this temperature.

Another major factor in the development of the wire process was the selection of the substrate metal. Tungsten and tantalum proved to be

unsuitable because free niobium deposited on them epitaxially prior to the nucleation of the Nb_3Sn phase. A cross section of such a deposit is shown in Fig. 4a. Large cracks are seen in the Nb_3Sn phase and a low rate of nucleation of Nb_3Sn is manifested by discrete bundles of Nb_3Sn crystals radiating from distinct points on the outer surface of niobium. These results indicated that substrates with β-tungsten structure were desirable to aid in the nucleation of Nb_3Sn. Commercially such substrates are not available. Hence, refractory metal substrates were considered which react with niobium to form a β-tungsten compound. Five metals belong to this category; they are rhodium, osmium, iridium, platinum, and gold[9]. When platinum wire was used as a substrate a single-phase deposit of Nb_3Sn was obtained, as shown in Fig. 4b. The columnar growth radiating from the substrate exhibits a preferred orientation in the [200] direction normal to the surface. The width of the columns determined by an electron microscope ranges between 750 and 1500 Å,[10] indicating a high rate of nucleation (approximately 10^5 nuclei per cm of the surface).

Additional examples of the nucleation process are shown in Fig. 5a and b for Nb_3Sn deposits on nickel (which does not form a β-tungsten structure with niobium) and gold-plated nickel ribbons, respectively. A striking similarity can be seen between the deposit on platinum (Fig. 4b) and gold (Fig. 5b), which strongly indicates that Nb_3Sn growth is preceded by the formation of β-tungsten structure compounds Nb_3Pt and Nb_3Au.

In addition to their role in the nucleation, the noble metals have favorable expansion coefficients, which are slightly larger than that of Nb_3Sn, thereby giving rise to "prestressed" Nb_3Sn deposit as the wire is cooled from its deposition temperature to ambient temperature.

C. Properties of Vapor-Deposited Niobium Stannide

Some of the physical properties of vapor-deposited niobium stannide appear in Table 1. The purity of the vapor-deposited Nb_3Sn was higher than that of the starting sintered material with respect to all non-gaseous impurities. One exception was silicon, which was probably introduced by reaction with the quartz apparatus. Data on the content of gaseous impurities are not available. Chemical analysis for tin and niobium were done by means of X-ray fluorescence technique in which sintered materials were used for calibration. Single phase, β-tungsten structure deposits on wire and ribbon substrates had compositions ranging between 76.2 and 81.5 atomic percent niobium as a consequence of changing the conditions in the deposition process. This composition range is in close agreement with the phase diagram proposed by Cuthill[12], who has shown that in the niobium-tin system above 863°C only one compound exists, with very nearly the same composition range as that given above.

Measurements of superconducting properties showed significant differences between the vapor-deposited and the sintered materials. There is a drastic but smooth decrease in T_c from 18 to 8°K corresponding to the compositional variation of the vapor-deposited materials given above. This is to be contrasted with only a minute variation in T_c for the sintered

TABLE I

Some Physical Properties of Vapor-Deposited Niobium Stannide

Nature of deposit	Single phase, β-tungsten structure
Lattice constant range	5.284 — 5.289 Å
Composition range	76.2 to 81.4 atomic percent Nb
Macroscopic density	8.80 g/cm^3
Lattice disorder	20 — 100 percent
Coefficient of expansion (20-1000°C)	7.1×10^{-6} $(°C)^{-1}$
Modulus of elasticity	9×10^6 psi*
Tensile strength	24,000 psi*
Resistivity (300°K)	12×10^{-5} (Ω-cm)

* Tentative values only.(11)

material in the same composition range[6]. The variation in T_c can be explained on the basis of lattice disorder and, in particular, on the basis of the relative occupancy of the tin sites by niobium. These results and their interpretation will not be discussed further since they are subject of another paper[13]. It is worth noting, however, that this is the first experimental evidence that microscopic disorder plays an important role in the superconductivity of Nb_3Sn, indicating that the simple concept of "electron to atom" ratio[14] alone cannot explain the superconductivity of this compound.

Critical current measurements as a function of magnetic field were made on wires and ribbons with cross-sectional area of niobium stannide ranging from 5×10^{-5} to 2×10^{-4} cm^2. Preliminary results reported previously[15] were comparable to published results for sintered materials[4]. With recent modifications in the deposition process, and the technique of establishing current contacts (total contact resistance $\approx$ 3×10^{-5} ohm) significant improvements in the critical current density (J_c) were realized. These results are shown in Fig. 6, which gives J_c data on vapor-deposited ribbon as a function of transverse dc field measured by Aron and Hitchcock[16] up to 93.5 kilogauss. These data are given for ribbons with T_c of 17.6°K and 14.6°K. The J_c for the ribbon with T_c of 14.6°K is significantly lower of the two, but even here characteristic "knee" in the J_c curve is not approached at the maximum field. Fig. 6 further shows published data for sintered Nb_3Sn wire[4]. Finally, measurements in a pulsed, longitudinal field of 170 kilogauss by Cherry[17] indicate J_c of 1.5×10^5 amp/cm^2 for a wire with T_c of 17.5°K.

The variation in the critical current density was measured in more detail at lower transverse dc fields for ribbons ranging in T_c from 8.2 to 17.6°K. A strong exponential dependence of J_c on T_c was found in accordance with the expression

$$\log J_c = 0.164\, T_c + 3.16 \qquad (8)$$

at a field of 7500 gauss. Although its theoretical significance is not known this behavior is noteworthy since it relates J_c over a long range of T_c of materials which are nearly identical from the standpoint of structure and chemical composition, thereby eliminating the influence of these parameters.

D. Nb_3Sn Solenoid

To demonstrate the usefulness of vapor-deposited niobium stannide in the construction of solenoids, coated ribbon, rather than the wire, was used because of its better mechanical properties, more convenient handling and higher packing factor. Typical cross-sectional dimensions of the ribbon substrate made of platinum are 0.070 cm by 0.0037 cm with the thickness of the Nb_3Sn deposit ranging from 0.0003 to 0.0010 cm.

Three sections of such ribbon totalling 450 meters have been wound into a solenoid. The solenoid form was made of an aluminum bronze alloy (Duronze 708), such that the coil had an inside diameter of 5.1 cm, outside diameter of 6.0 cm and a length of 6.3 cm. The ribbon was uninsulated, except for a thin oxide coating, which allows for only resistive contacts, and 0.0006-cm thick Mylar sheet between consecutive layers. Fig. 7 shows

a photograph of the first section of the solenoid and a cross sectional view of the ribbon used. The performance characteristics are given in Table II.

TABLE II

Performance of Nb_3Sn Solenoid

Section	No. of Turns	Quenching* Current (Amp)	J_c (amp/cm^2)	Field Observed Gauss	Field Calculated Gauss
Inside	552	35	2.5×10^5	10,360	11,300
Middle	930	17	1.4×10^5		
Outside	1256	32	2.7×10^5		

*At 10,300 gauss, all sections operating in parallel. At the same field the J_c of short test pieces of ribbon was 3.2×10^5 to 4.0×10^5 amp/cm^2. The T_c of the ribbon ranged from 14.6 to 15.8°K.

The solenoid was operated repeatedly both with and without protective shunts placed in parallel with each section and through numerous current quenchings and temperature cyclings. The so called "training effect" was not experienced. The observed range of current densities (See Table II) represents the highest J_c for a superconducting solenoid reported to date.

Acknowledgments

The author is grateful to Dr. Fred Rosi for his motivation and enthusiastic support of this work. Acknowledgments are due to Mr. J.L. Cooper for his valuable assistance and significant contributions in the development of the process. The author wishes to acknowledge Dr. G.D. Cody for his constructive discussions and his part, along with Messrs. M. Rayl and G.T. McConville, in the low temperature measurements, and Dr. J.G. White and Mr. R. Paff for the performance of X-ray diffraction measurements.

Special recognition is due several of the members of RCA Electron Tube Division, Harrison, N. J., in particular to Messrs. N.S. Freedman and K. Strater for their close cooperation, Dr. E. Bertin for his performance of X-ray fluorescence analysis, Mr. T. Berry for his metallographic work and Mr. R. DeLong for furnishing substrate materials.

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A = KANTHAL RESISTANCE FURNACE

B = REACTION TUBE, QUARTZ, L-120cm, I.D. 26mm

C = QUARTZ CHLORINATION TUBE, I.D. 10mm

D = CHLORINE INLET

E = HYDROGEN INLET

F = POWDERED, SINTERED Nb_3Sn

G = EXHAUST GASES

H = GAS-PHASE DEPOSITED Nb_3Sn CRYSTALS

I = GAS-PHASE DEPOSITED Nb_3Sn FILMS INSIDE 8cm QUARTZ TUBE 15mm I.D.

J = Nb_3Sn FILMS CONTAINING BLACK IMPURITIES

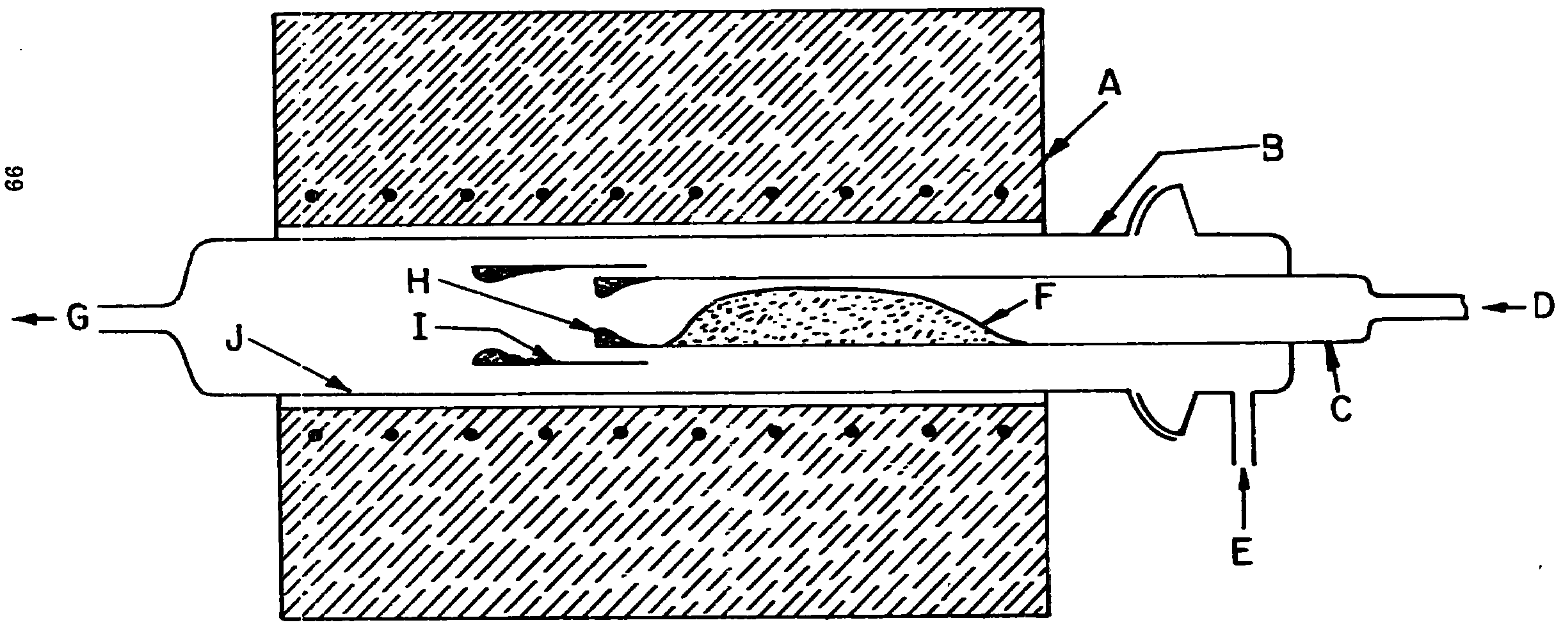


FIG. I SCHEMATIC DIAGRAM FOR VAPOR DEPOSITION OF Nb_3Sn

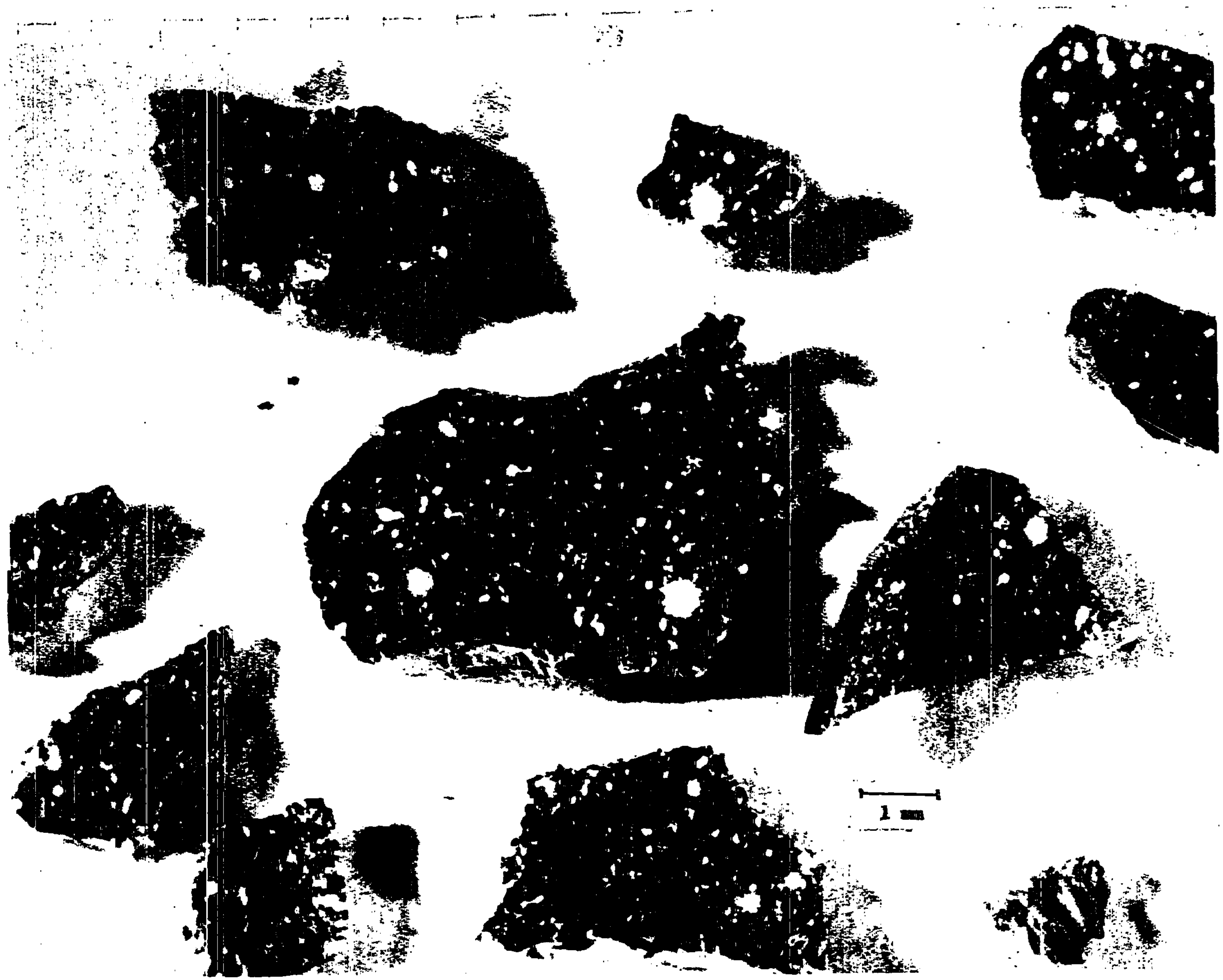


FIG. 2 POLYCRYSTALLINE VAPOR DEPOSITED Nb_3Sn

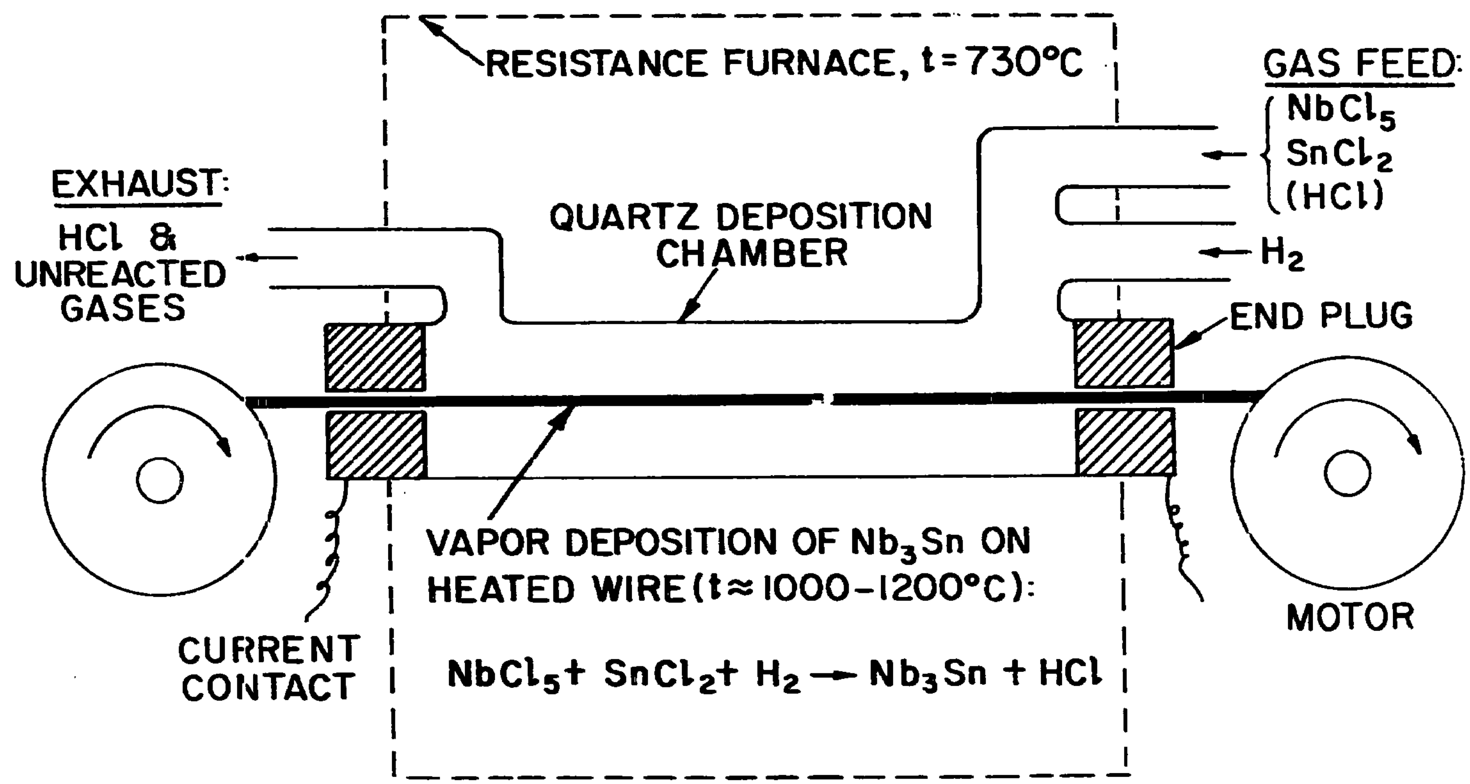
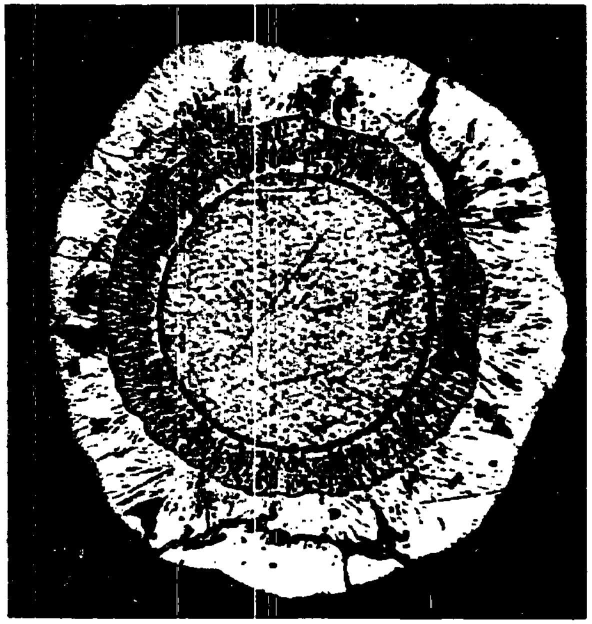
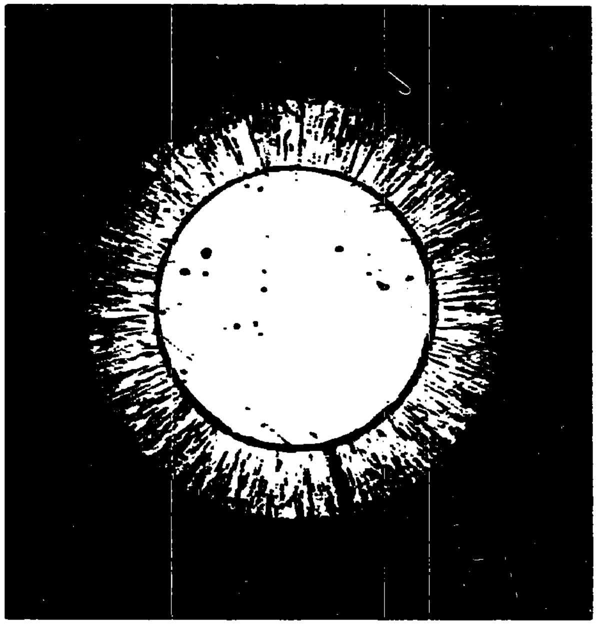


FIG. 3 SCHEMATIC DIAGRAM FOR CONTINUOUS VAPOR DEPOSITION OF NIOBIUM STANNIDE WIRE OR RIBBON



(a)



(b)

FIG. 4 (a) VAPOR DEPOSITION OF NIOBIUM STANNIDE ON TANTALUM WIRE (INNER DEPOSIT IS FREE NIOBIUM, OUTER DEPOSIT IS NIOBIUM STANNIDE). WIRE SUBSTRATE DIAMETER = 0.018 CM.

(b) NIOBIUM STANNIDE ON PLATINUM WIRE. WIRE SUBSTRATE DIAMETER = 0.018 CM.

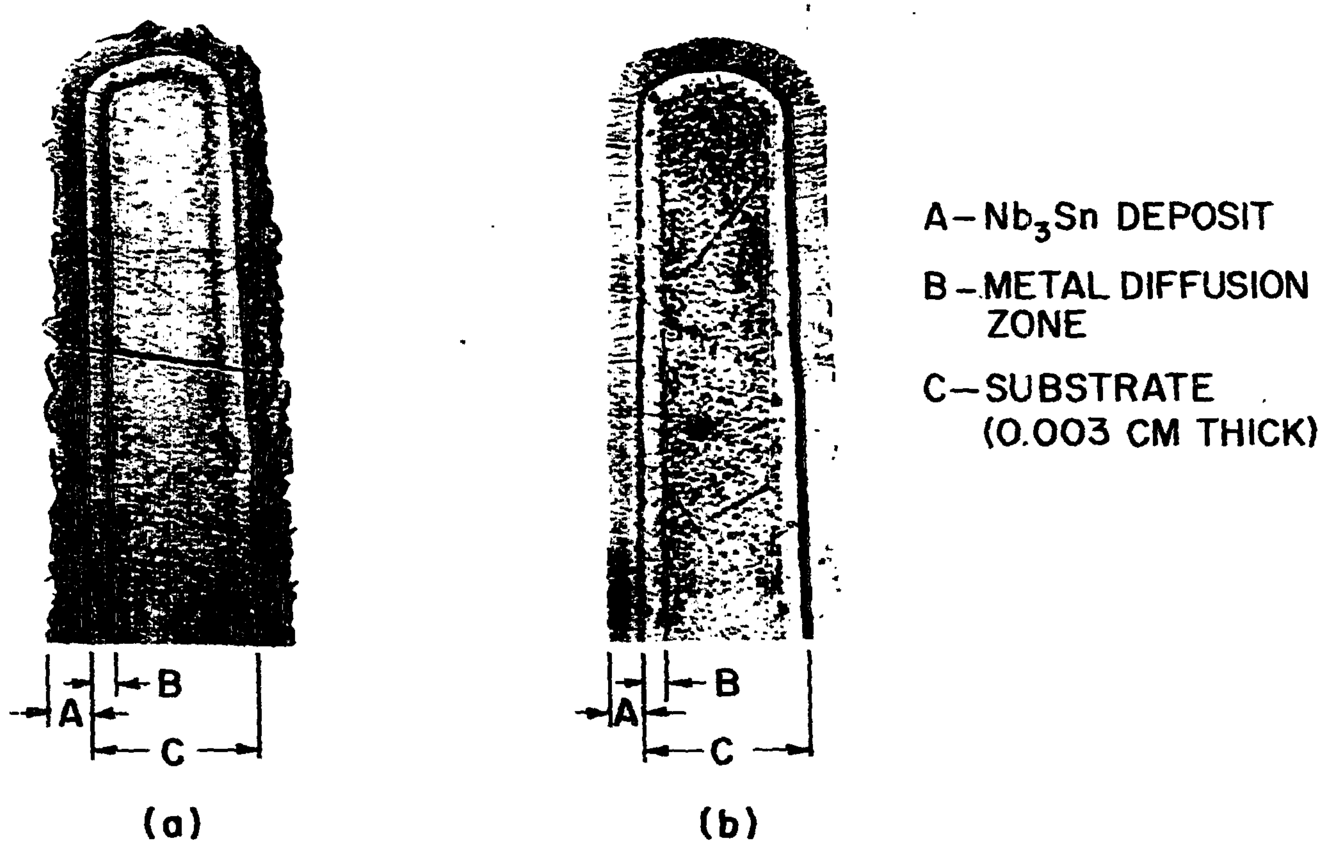


FIG. 5. NIOBIUM STANNIDE VAPOR DEPOSITED ON
(a) NICKEL
(b) GOLD-PLATED NICKEL

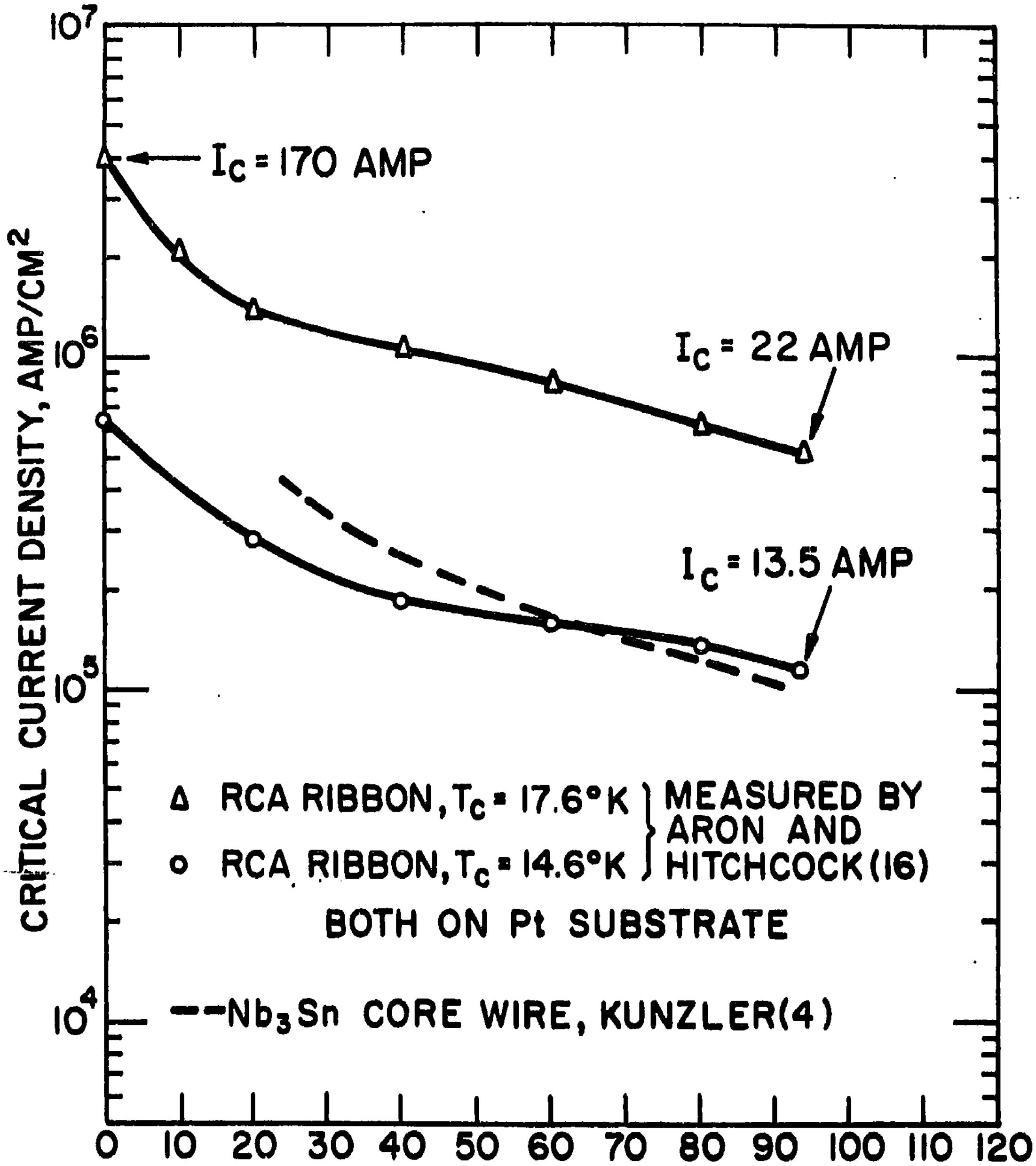


FIG. 6 APPLIED TRANSVERSE DC MAGNETIC FIELD, KILOGAUSS

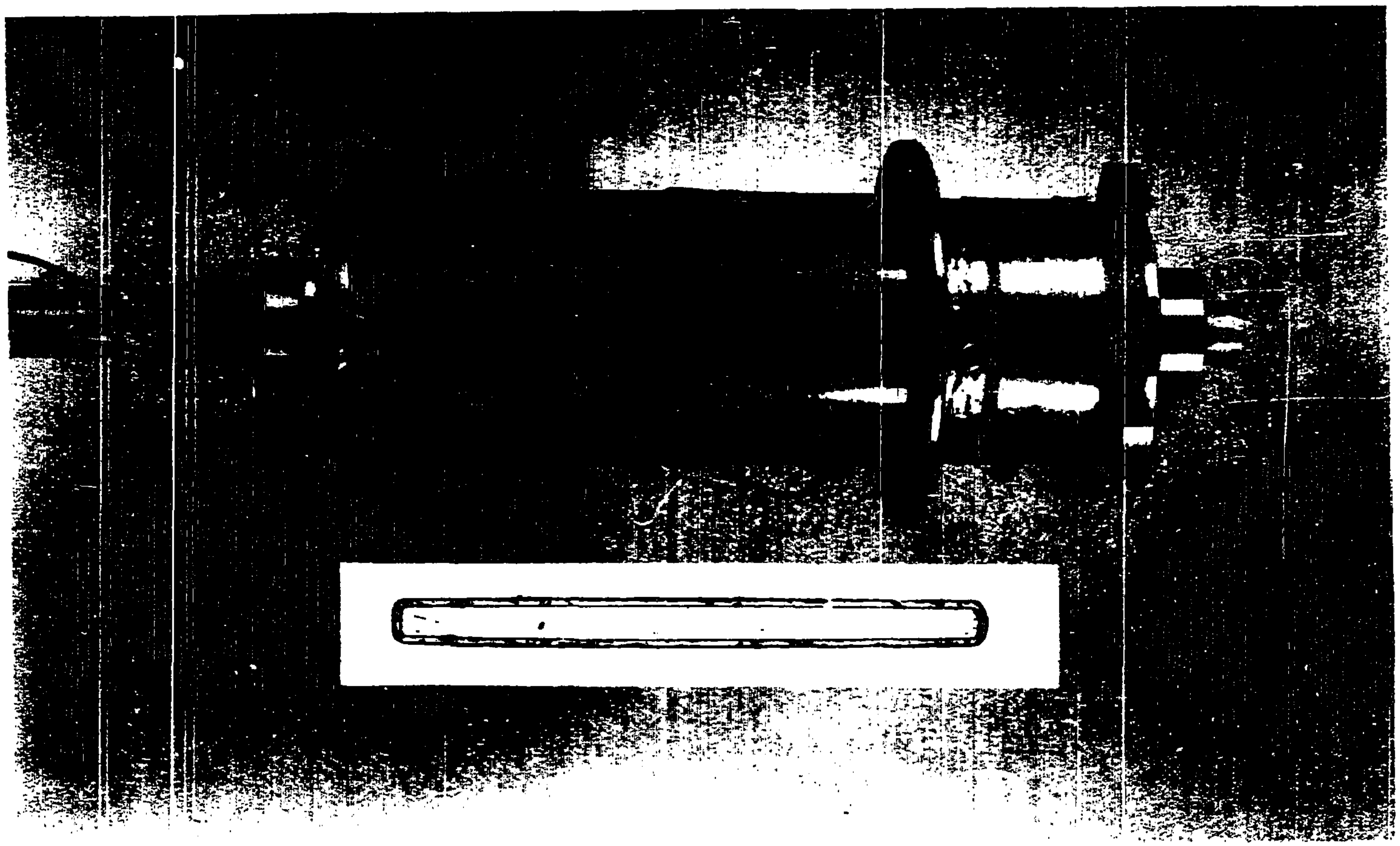


FIG. 7 (a) FIRST OF THREE SECTIONS OF A 10,360 GAUSS SOLENOID WOUND WITH VAPOR-DEPOSITED NIOBIUM STANNIDE RIBBON.

(b) CROSS-SECTIONAL VIEW OF THE RIBBON USED – 0.072 CM x 0.0055, DEPOSIT THICKNESS = 0.0008 CM.

ENERGY STORAGE IN SUPERCONDUCTING SOLENOIDS

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Westinghouse Electric Corporation

In a magnetic field of 100,000 gauss, we have about 40 joules per cc or about a million joules per cubic foot. The largest superconducting magnets so far constructed have stored about 50,000 joules.

We shall consider a long solenoid of internal radius r and winding thickness t cm constructed from square conductors of edge w cm. We shall assume essentially 100 per cent packing factor. We define the quantities

J = solenoid current density (amperes per cm^2)

H = solenoid field (gauss)

T = hoop stress in winding (dynes per cm^2)

P = pressure of field (dynes per cm^2)

Consider a slice through the solenoid one cm in length. The basic equations are:

$$T\,t = P\,r \qquad (1)$$

$$P = J\,t\,H/20 \qquad (2)$$

$$H = (4\,\pi/10)\,J\,t \qquad (3)$$

Eliminating P and J we obtain

$$T = \frac{H^2}{8\pi}\,\frac{r}{t} \qquad (4)$$

The energy stored in one cm length of the coil

$$U_1 = \frac{H^2}{8\pi}\,\pi r^2 = \pi\,r\,t\,T \ \text{ ergs} \qquad (5)$$

If the cost of the winding material is A cents per cubic centimeter, the cost of the material in the one cm long slice

$$C = A\, 2\pi\, r\, t \quad \text{cents} \tag{6}$$

Thus, the price of the energy storage

$$\frac{C}{U_1} = \frac{2A}{T} \quad \text{cents per erg} \tag{7}$$

Let us use the symbols

S = cost of material in dollars per pound

T' = hoop stress in psi

We have the conversion formulae

$$840\, S = 454\, A$$

$$T = T'\, 6.9 \times 10^4$$

Thus

$$\frac{C}{U_1} = 536\, \frac{S}{T'} \quad \text{cents per joule} \tag{8}$$

Assuming a yield stress of about 200,000 psi and the present price of Nb + 25 per cent Zr as $400 per pound, we obtain

$$\underline{C/U_1 = 1.1 \text{ cents per joule}}$$

This, of course, ignores all the refrigeration costs. Notice that the energy cost is independent of H and the coil dimensions if we stress the solenoid to its ultimate yield stress. If a support structure of non-superconducting material can be used, C/U_1 could be appreciably reduced, perhaps by a factor of 4. With mass production of wire, S could be lowered by a factor 10. Hence, we could hope to bring C/U_1 down to about 0.025 cents per joule by further development. However, this still ignores refrigeration costs.

Secondary Boundary Conditions

If we also require the maximum energy per unit volume, this automatically maximizes the field H. We shall adopt an idealized wire characteristic with a constant critical current density J_c up to a maximum field H_M, above which J is zero.

Then, for maximum energy per unit volume, from equation (4):

$$\frac{r}{t} = \frac{8\pi T}{H^2} \tag{9}$$

For a maximum H of 10^5 gauss, this sets r/t. We have

$$\left(\frac{r}{t}\right)_{Min} = \frac{8\pi \times 2 \times 10^5 \times 6.9 \times 10^4}{10^{10}} = 35$$

For maximum energy per unit volume, the coil radius should be 35 times the winding thickness.

The inductance per unit volume L_1 is given by

$$\frac{1}{2} L_1 I^2 = H_M^2/8\pi$$

Since I is Jw^2 and H_M is given by equation (3),

$$L_1 = 4\pi \times 10^{-9} \frac{t^2}{w^4} \text{ henries/cc}$$

Thus, for any conductor size we minimize L_1 by minimizing t. However, from equation (3)

$$t = \left(\frac{10}{4\pi}\right) \frac{H_M}{J}$$

so that to minimize t we must maximize J. In practice, we can expect $J = J_c \sim 10^5$ amperes/cm^2 which sets

$$t_{Min} = 1 \text{ cm.}$$

Summary

(a) Minimum cost per unit energy requires that the coil operate under maximum possible hoop stress. At present prices, this results in a cost of one cent per joule, ignoring refrigeration. This price could probably be reduced by a factor of 40.

(b) Maximum energy per unit volume sets the radius of the solenoid at about 35 times its winding thickness. Under these conditions, it stores about 10^6 joules per cubic foot (H_{Max} = 100,000 gauss).

(c) Minimum inductance per unit volume sets the thickness of the winding at about one cm.

Major Problem Areas:

(1) The cool-down refrigeration capacity will have to greatly exceed the static capacity. This could be very costly.

(2) The present production of niobium in the United States is relatively small. The energy stored per pound of niobium-zirconium alloy is about 40,000 joules and the annual production of the alloy is about 1000 pounds, so that annual production only allows the storage of 40 million joules.

(3) Superconducting solenoids tend to normalize under high dH/dt rates. It may be very difficult to get the energy out in very short times without dumping within the coil itself.

February 18, 1963

A CRYOGENIC SYSTEM TO REFRIGERATE A SUPERCONDUCTING INDUCTOR

Air Products and Chemicals, Inc.

Research and Development Department

February 21, 1963

Summary

This presentation discusses the cryogenic system necessary to refrigerate at 4.4° Kelvin a superconducting inductor capable of storing the required amount of energy. The magnet, which is a hollow cylinder, 0.8 centimeter thick and about seven meters in diameter and seven meters long, is contained in a spherical dewar 32 feet in diameter. Low temperature (4.4°K) refrigeration can be furnished for this system by a 1.4 KW helium refrigerator operating only two percent of the time, if certain technical problems are solved. Such a refrigerator could, therefore, cool a multiplicity of these systems and still retain a reasonable down-time for routine maintenance. The number of magnets and, hence, dewar systems necessary is, of course a function of the time required to recharge the discharged inductor and the number of repetitive discharges sought.

The uninstalled cost of the 1.4 KW refrigerator-liquefier is about $400,000 and the superinsulated sphere cost is about $300,000. In this design, about $100,000 is allowed for a helium inventory of 10^6 cubic feet, but this value could unquestionably be reduced by appropriate design changes. In the same fashion, about $200,000 is allocated for ancillary equipment, including non-cryogenic storage for the helium supply. This figure would also be subject to reduction by appropriate design modifications. Nevertheless, a total cost for a single, installed system of the magnitude of 10^6 dollars can be estimated. Although a multiplicity of such would be required, the number would not appear likely to become a direct multiple of the number of

discharges. On this basis, it does not seem that the cryogenics will be controlling in cost of the overall system.

Although most of the cryogenic system for magnet cooling is of conventional design not requiring research studies for application, several problem areas are apparent in relating the cryogenics to the inductor. The most prominent problem is that of electrical leads from the magnet, since such leads increase the refrigeration load tremendously. Detachable or low thermal conductivity leads are required and should be sought. Engineering optimization of the cryogenic system should also be studied. It is important to balance the refrigeration size against the heat load requirements, and for this purpose it is desirable to know the number of inductors required and the effect on their size of reducing the discharge time to milliseconds. The total liquid nitrogen requirement of the system is also important to appraise, to allow a firm estimation of the cost.

A CRYOGENIC SYSTEM TO REFRIGERATE A SUPERCONDUCTING INDUCTOR

Air Products and Chemicals, Inc.

Research and Development Department

I. INTRODUCTION

The primary objective of the following presentation is to discuss the principle features of a cryogenic refrigeration system for environment control of a superconducting magnet containing stored energy. The magnet system is unusual in size. Before discussing the refrigeration system, certain design criteria are identified through consideration of the parameters of the magnet design and use. Hence, the first portion of the paper deals with the magnet design and the second with the cryogenic system, its design and cost.

A number of the features of the solenoid design seem well beyond the state of present materials. Nevertheless, the magnet has been designed, using performance as a guideline rather than materials. No attempt has been made to consider the problems of power generation for the solenoid. With the nature of the load to which the power is to be supplied unspecified, no consideration has been given to the influence of heat transfer from the load on the refrigeration system. With these rather bold assumptions, a cryogenic system has been designed.

II. DISCUSSION

The Magnet Characteristics and Configuration

The problem of large energy storage in a superconducting magnet followed by release in very short time intervals can be approached considering first the problems inherent in transfering energy from an inductor to a loading resistor. If an inductance (L) carrying a current (I) is suddenly placed across a resistance (R),

the energy (U) delivered to the resistance in a time of t seconds is given by

$$U = U_o (1 - e^{-2Rt/L})$$

where U_o is the initial energy stored in the inductor. In order to keep the initial energy (U_o) as small as possible for a given U, the factor $e^{-2Rt/L}$ should be as small as possible. The following table give the factor $1 - e^{-2Rt/L}$ as a function of R/L for t = 1 second:

R/L	$e^{-2R/L}$	U/U_o
0.00	1.00	0.00
0.25	0.61	0.39
0.50	0.37	0.63
0.75	0.22	0.78
1.00	0.13	0.87
1.25	0.08	0.92
1.50	0.05	0.95

The energy stored (U_o) in the inductor can be calculated by

$$U_o = LI^2/2$$

The maximum voltage (V_o) that will appear across the inductor or resistance during discharge is given by

$$V_o = I\,R$$

Accordingly,

$$\frac{R}{L} = \frac{I\,V_o}{2\,U_o} \approx 1$$

for 90% of the initial stored energy (U_o) to be dissipated in the resistance (R) in one second.

The required size for a superconducting magnet may be estimated by considering the critical field (B_c), the energy stored (U), and the permeability (μ_o). On Figure 1 a solenoidal magnet of inside diameter a, winding thickness c, and length b

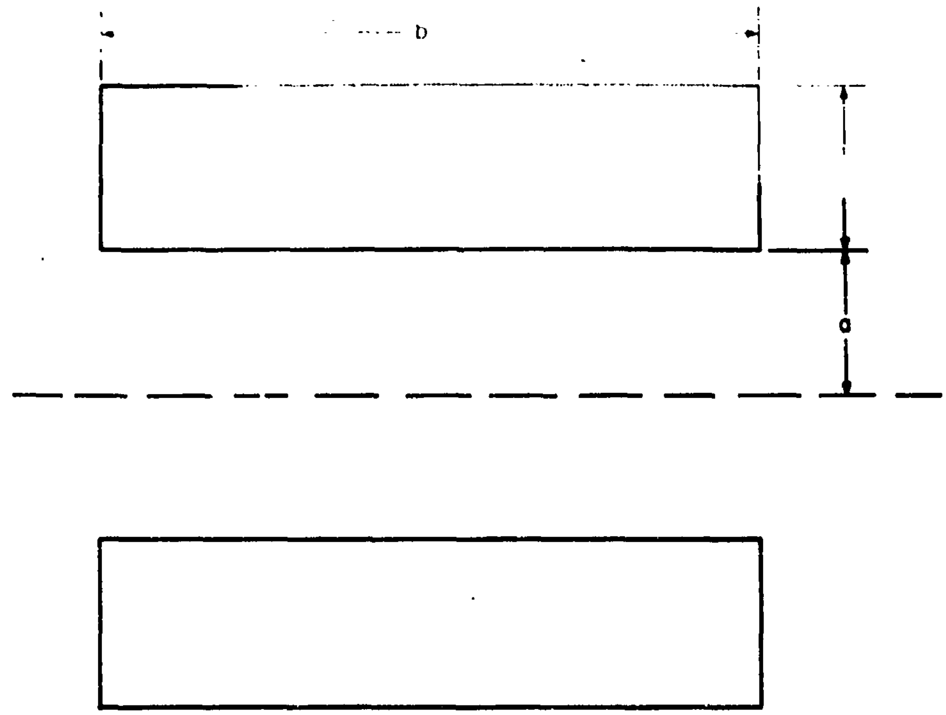

Fig. 1. Schematic of the solenoid coil

is shown, which will store an energy U_o. For simplicity in estimating the size, the finite length of the coil is ignored so that the magnetic field can be taken to be uniform. The total energy stored in the coil is

$$U = \frac{1}{2} \frac{a^2 b}{\mu_o} B_c{}^2$$

where B_c is taken as the critical field of the superconductor. It can also be written that

$$B_c = \frac{\mu_o n I}{b}$$

where n is the number of turns on the solenoid and μ_o is the permeability of a vacuum. This may be written

$$B_c = \mu_o \, c \, f \, I_c$$

where $f I_c$ is the current density in the windings, f being the fraction of the critical current, and I_c the critical current density. If $2a = b$, a solenoid results with inside diameter and length of 6.8 meters and a layer of superconducting windings 0.8 cm thick.

The coils will consist of about 60 turns of superconductors 0.8 cm thick and 12 cm wide in cross section. The weight of the solenoid will be about 10^4 kg.

Since the recovery time of the inductor, or that time required to charge it in preparation for another discharge, is difficult to assess, the system has been designed for a single discharge case. On this basis, the calculated refrigeration load can be converted to the actual requirements by an appropriate factor, as a first approximation.

The heat load on the refrigerator system required will be determined in part by the heat dissipation in the bus bars during operation.

<u>The Refrigerator</u>

The refrigerator problem for the superconducting solenoid and bus bars necessary to carry the discharge current has been analyzed using the following conditions:

<u>MAGNETIC DESIGN PARAMETERS</u>

Size of Magnet	=	6.8 meters diameter by 6.8 meters long
Temperature of Magnet	=	4.4°K
Weight of Magnet	=	10,000 Kg

A schematic drawing of the magnet and its containment vessel is shown on Figure 2. The magnet is located inside a large double-walled spherical dewar of about 32 feet diameter and is supported from above by comparatively thin stainless steel rods. The support rods and the electrical leads are carried in extended necks thru the

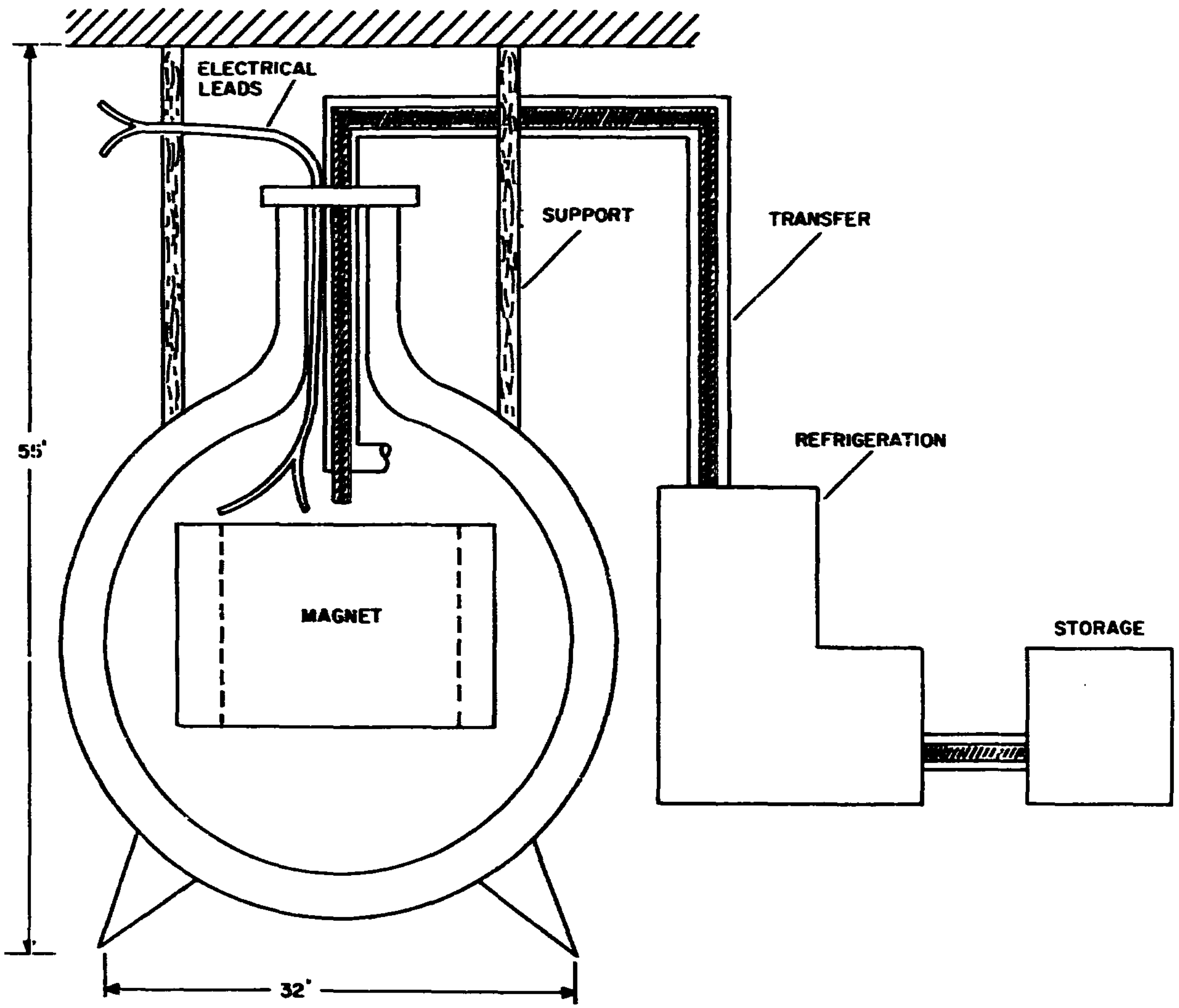

Fig. 2. Schematic of the cryogenic inductor system

top of the sphere. A helium refrigerator-liquefier is placed as a separate unit at the side of the sphere, with cold helium being exchanged between the refrigerator and the sphere thru shielded transfer lines. Liquid nitrogen is extensively used for cooling and shielding purposes.

The refrigeration load after cool-down consists of various continuous heat leaks and an intermittent electrical load during discharge of the magnet.

The electrical load is due to the resistance of the leads which operate in the temperature range between 5°K and room temperature and are not superconductive. Depending somewhat upon the nature of the external electrical load, superconducting leads might be feasible. This possibility is sufficiently speculative, however, that it has not been considered in this case.

It has been assumed that the refrigeration load caused by the magnet charging apparatus may be neglected. The refrigeration load is adsorbed as far as possible by the liquid nitrogen cooling. The helium refrigerator supplies cooling at temperatures below liquid nitrogen temperatures.

The design of the electrical leads is a major problem. They should have a high thermal resistance and at the same time a low electrical resistance, conditions which are somewhat incompatible with current materials. If the leads remain connected to the low temperature level, a high heat leak results and the refrigerator has to be in virtually continuous operating during the stand-by period. If the mechanical problem of disconnecting and connecting the leads can be solved, the refrigerator-liquefier need be in operation during only a fraction of the stand-by period. A very likely approach to solving the lead problem is to avoid identifying the electrical and thermal switches in the leads as being one and the same. In other words, the inductor can be brought into outside contact with the load in two steps, first by establishing thermal

contact to the low temperature through appropriate conductors and then by switching in electrically.

One feasibility study has been concerned with the heat leak when the leads remain connected. The more cryogenically practical alternate in which the leads disconnected except during discharge is also calculated. As the electrical load is applied only intermittently, much small continuous heat leak by conduction results. Nevertheless, to meet the electrical requirements the leads tend to become quite large. A schematic of the leads is shown in Figure 3. For this design the leads have been calculated to consist of three copper sections, each 10 ft long. The cross sectional areas of the three sections are 0.8, 0.4, and 0.4 ft^2. Liquid nitrogen cooling is used between sections 1 and 2, and by the refrigerator at about 20°K between sections 2 and 3. Section 3 is partially immersed in a liquid helium bath.

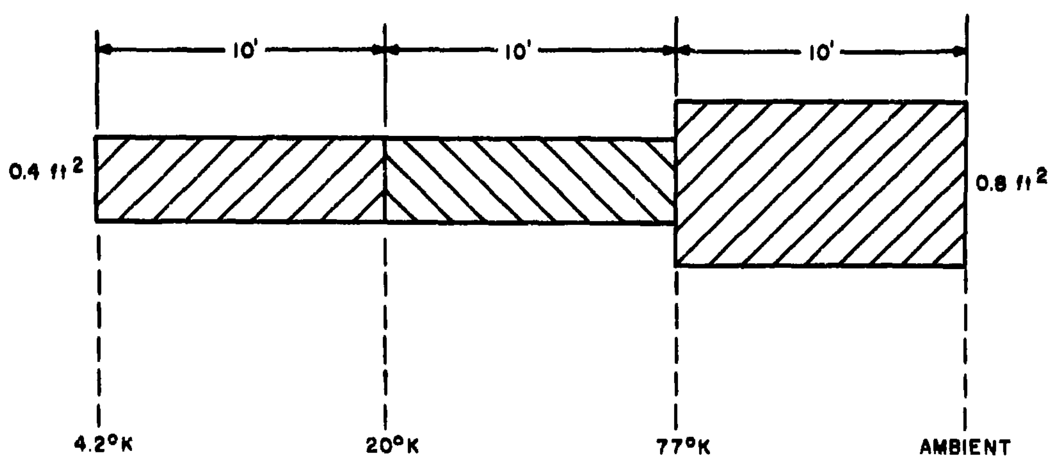

Fig. 3. Schematic of the electrical leads

The electrical heat loads are not absorbed immediately by the refrigerator. They are temporarily absorbed by the heat capacity of sections 1 and 2, heating up the lead by 20 - 30°F, and will eventually evaporate the cryogenic fluid. The refrigerator will gradually absorb the electrical losses after the discharge period.

Considerable optimization work remains to be done on the leads both in materials and design.

Case I. Connected Leads

With connected leads and nitrogen shielding but without the use of superinsulation, the following heat leaks by conduction can be estimated:

Heat Leak to 4.2°K

Sphere and Magnet Support	500 BTU/hr
Electrical Leads	1240 BTU/hr
Refrigerator and Transfer Lines	500 BTU/hr
	2240 BTU/hr

Heat Leak to 20°K

Electrical Leads	4600 BTU/hr
Refrigerator and Transfer Lines	500 BTU/hr
	5100 BTU/hr

Heat Leak to 77°K (liquid nitrogen)

Sphere and Magnet Support	15,000 BTU/hr
Electrical Leads	8,600 BTU/hr
Refrigerator and Transfer Lines	13,300 BTU/hr
	36,900 BTU/hr
	(15.3 moles of LN_2/hr)

The electrical heat generated during a discharge is as follows:

Lead Section 1	1960 BTU
Lead Section 2	220 BTU
Lead Section 3	54 BTU

The total helium refrigeration load listed above approximately equals the capability of a helium refrigerator rated as 1.0 KW at 4.2°K and utilizing a 400 horsepower compressor. In stand-by condition the refrigerator would operate about 2 per cent of the time while during discharge of the magnet the full capacity would be needed. Initially, tons of liquid nitrogen have to be expended in order to cool the system to liquid nitrogen temperatures where the bulk of the heat has been removed.

To obtain a cool-down time of a few hours and absorption of the electrical loss within minutes to place the system in readiness quickly would call for considerable extra refrigeration capacity. If the electrical discharge could be reduced, the electrical heat (I^2R) would fall. Of course, the leads could then be designed considerably smaller, resulting in a smaller continuous heat leak but the same electrical heat loss. The net result would be to reduce the refrigerator size by one-half (0.5 KW at 4.4°K).

Case II. Disconnected Leads

If the system is to be kept in readiness indefinitely with minimum operation of the refrigerator-liquefier, the heat leaks must be reduced drastically. Disconnecting the electrical leads appears to be an absolute necessity. Also, insulation of the sphere should be improved by the use of superinsulation. The use of liquid hydrogen would be very attractive from a refrigeration standpoint, but that will not be injected at this stage.

By this means it should be possible to reduce the total heat leak to the sphere, inside which a helium atmosphere of 4 - 5°K is kept, to a value below 100 BTU/hr. The refrigerator-liquefier will then charge enough liquid helium to the sphere to make a stand-by period of days or even weeks possible without refrigerator operation.

A heat leak of 100 BTU/hr will evaporate about 37 lb/hr of liquid helium. For a standby period of 2 weeks (336 hrs), 12,432 lb. or 12.43 m^3 of liquid helium has to be provided. This is a small amount compared to the volume of the sphere (15,000 ft^3).

A liquefier nominally rated at 1.4 KW at 4.4°K is capable of providing 200 lb/hr of liquid helium or as much as 1750 lb/hr with full return of cold vapor from the sphere.

Such a liquefier would be in operation as little as seven hours in a two week period, or only about 2% of the time. On this basis, the net running time would only total about 200 hrs. per year. A much smaller liquefier could be used, or the same liquefier could cool a multiplicity of such magnet-dewar devices. The average maintenance period for such refrigerators is currently 1500-2000 hours when non-lubricated compressors are used. Hence, reliability should be quite high and routine maintenance easily scheduled for down periods.

However, the initial cool-down duty, which includes filling the sphere with a very large amount of cold helium vapor, is a formidable task for a marginal liquefier. An otherwise empty sphere would contain about 18,500 pounds of cold helium vapor. Various steps to shorten the cool-down can be taken, such as reducing the helium inventory, achieving the cool-down of the large masses by the refrigerator from liquid nitrogen temperature, or shipping in liquid helium at start-up. In this way the refrigerator will be of a more modest size. A more detailed study would be needed to determine the minimum refrigerator which could be used for reasonable overall operation.

Cost Analysis

A rather rough cost estimate of the installation and use of such cryogenic apparatus is possible. The 1.4 KW refrigerator-liquefier would cost about $400,000 complete but not installed. Other major components of the system could be estimated as $300,000 for the superinsulated sphere and about $100,000 for the 10^6 ft^3 of helium inventory. With this amount of helium a breakdown causing vaporization of the helium could prove quite costly. Accordingly, additional facilities would be desirable to provide

for high pressure storage of helium. The total investment in cryogenic equipment would be at least $1,000,000.

The operating costs of the cryogenics are not unreasonably large. They involve operator attendance (part time), maintenance of machinery (compressor and expansion engines once a year), 450 KW of electricity for the compressor (part time), ten dollars for lost helium every hour of compressor operation, and about 44 gal/hr of liquid nitrogen, and close to 10 tons of liquid nitrogen for initial cool-down.

Obvious Improvements

This study has been concerned with feasibility and rough estimation. A more detailed analysis would unquestionably improve the system.

For example, it can readily be shown that the heat leak by radiation through the vacuum and shielded wall of the sphere is about 10 BTU/hr compared with the total heat leak of 100 BTU/hr. Most of the heat leak is through the various connections on top of the sphere, such as transfer pipes, electrical lead connections, and supports. In all probability, much of the heat leak into the sphere could be cut to reduce the 100 BTU/hr assumed. A reduced heat leak would, of course, reduce the refrigerator-liquefier requirement. The use of liquid hydrogen for cool-down and shielding would be of help, and the continuous use of liquid nitrogen could be reduced by placing super-insulation between the liquid nitrogen shield and the outer wall of the sphere. At the limit we may anticipate a liquefier only one tenth of the proposed size.

III. CONCLUSIONS

The cryogenic system associated with a superconducting inductor of the dimensions chosen is entirely feasible for earthbound application and not unduly expensive, either in investment or operating cost. Unquestionably, the major limitation to the entire system lies in the inductor rather than the cryogenics.

SUMMARY

Robert C. Hamilton

Institute for Defense Analyses

Superconducting coils have been fabricated in the laboratory as large as 5 in. in diameter, storing 15,000 joules. Larger superconducting coils are being built at present which will store more than 10^5 joules. To meet the energy storage requirements discussed in this symposium it will be necessary to extend the energy storage capacity of superconducting coils six to seven orders of magnitude.

Preliminary design estimates indicate that large superconducting inductive energy storage coils can store 10^{12} joules in a coil with a diameter of 115 feet and a length of 58 feet, weighing 2.5×10^6 lb. The titanium pressure-bearing shield required to supply necessary coil strength would weigh 15×10^6 lb. Comparatively speaking, the refrigeration weight is negligible. The power plant weight is a function of the charging time allowed.

Superconducting coil systems provide approximately 10^6 joules/lb compared to 10^3 joules/lb for large ambient temperature inductors. It is estimated that a superconducting inductive energy storage system having 10^{12} joules would cost from \$250 - \$350 $\times 10^6$ not including the cost of the MHD generator power source. The battery or MHD generator power source with an ambient temperature inductor will cost substantially less; that is, 1/3 to 1/6 of the cost of the superconducting inductive energy storage system.

The unknown ability of the superconducting coil to deliver its energy in times of the order of a millisecond may limit its attractiveness for this application.

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3. "A Superconducting Magnet for MHD Power Generation" by Z. L. L. Stekly, W.N. Latham and D. Hritzay, Avco-Everett Research Laboratory, 4th Symposium on the Engineering Aspects of MHD, Sponsored by the University of California, April 10-11, 1963 - I.E.E.E.

IV MAGNETOHYDRODYNAMICS

HIGH POWER SHORT DURATION MHD POWERPLANTS

By Stuart Hamilton, Pratt & Whitney Aircraft

Presented At Institute of Defense Analyses, February 5, 1963

Introduction

For the last three years, Pratt & Whitney Aircraft has been investigating for the Rome Air Development Center the production of large quantities of electrical power. Magnetohydrodynamic energy conversion has been selected on the basis of low cost and startup time. The contracts are funded under Project Comet. The purpose of the first contract was to indicate whether or not MHD was a technically and economically feasible method for generating large amounts of power on instant demand. The purpose of the second contract was to develop the technology necessary for the development of MHD generators and for the study of associated microwave tubes to provide large amounts of coherent directed microwave energy. Subcontractors for the microwave studies were Litton Industries and Raytheon. Figure 1 shows an artist's representation of a 1000 megawatt installation.

Optimization for High Power Density

High power density is the obvious key to low powerplant cost, light weight and compact installation. Our system studies indicate that highest power density is obtained under conditions of high supersonic flow in the MHD channel, Figure 2. This condition is accompanied by unusually high voltage gradients in the channel. These gradients are particularly high in the streamwise direction, Figure 3. If high wall resistivity is not maintained, much of the power developed will be shorted out in the generator walls, Figure 4. High resistivity ceramics appear to be the most suitable wall material for maintaining the required voltage gradients. High wall temperature was selected for

the following reasons: Condensation of seed material on the walls tends to short out the power. High wall temperature reduces cooling requirements, Figure 5. High wall temperature reduces heat loss which has a deleterious effect on plasma electrical conductivity and power density, Figure 6. Ceramics operating at high temperature have therefore been selected for the generator wall material.

Developing Hardware for High Power Density

Although ceramics have high melting points, high resistance to corrosion and oxidation, and high electrical resistivity, they tend also to be brittle and to lose their electrical resistivity at high temperatures. Under RADC and company sponsorship P&WA has conducted a program aimed at the development of materials superior to commercially available ceramics. Unique design techniques utilizing ceramic walls have been evolved and evaluated on test in MHD generators. Some of the data from the materials program are shown on Figure 7. As a result of the optimization studies, the materials program, and the MHD generator design techniques, P&WA has been able to generate 800 kilowatts per cubic feet with a magnetic field strength of only 21,000 gauss. At this power density we have simultaneously been able to make duration runs of one and one-half hours as limited by the available fuel supply at the test stand, Figure 8. Our experience with this program indicates that it is important to demonstrate durability on a design which is capable of withstanding the voltage gradients required for high power density. And it is equally important to demonstrate high power density on a generator which is capable of extended duration running. Only the simultaneous demonstration of durability and high power density is considered a valid proof of generator performance.

Costs

Based on a performance optimization for minimum cost of hardware plus supplies for 20 hours of projected operation and a mechanical design philosophy evaluated

on rig tests, we have made a detailed design layout of a 1000 megawatt generator and associated equipment. The cost of this design has been estimated for planning purposes. Including foundations, on-site oxygen plant, oxygen and fuel storage tanks, pumps and all other auxiliaries and tooling, the first unit cost for a 1000 megawatt generator is estimated to be approximately $10,000,000. In view of the tooling cost, subsequent units should cost somewhat less. Smaller generators will cost somewhat more on a per-kilowatt basis.

Operating cost is less than 10¢ per kilowatt hour. Since the units were not designed with low weight as an objective it is not reasonable to take the design weight as any indication of the weight for an airborne powerplant. It appears, however, that even with a radically lightened design, the total weight of a 1000 megawatt powerplant and 15 minutes of fuel supply would exceed the capacity of present airplanes.

Experience has indicated that the development of large powerplants costs something in the order of magnitude of $100,000,000. This cost can be minimized by adequate component testing in small sizes over a period of years before the large investment is committed. Small scale component test programs can be handled with yearly costs in the range of several million dollars in the period prior to commencement of a full scale powerplant development. Large powerplant developments can normally be expected to take approximately five years or more depending on the complexity of the powerplant and the degree to which the state-of-the-art must be advanced. The development of large powerplants of any type, MHD or otherwise, to operate with hot, erosive, corrosive, acoustically noisy gases requires large facilities and extensive test programs. It is recommended that small-scale generator programs be pursued as soon as possible to assure that high power generators will be available for use and for application development before 1970 and to keep the overall program costs as low as possible.

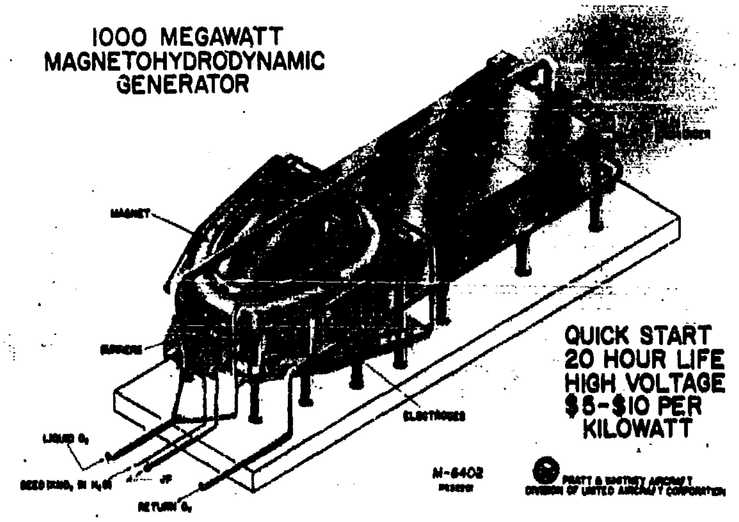
1000 MEGAWATT
MAGNETOHYDRODYNAMIC
GENERATOR
QUICK START
20 HOUR LIFE
HIGH VOLTAGE
$5-$10 PER
KILOWATT

Fig. 1.

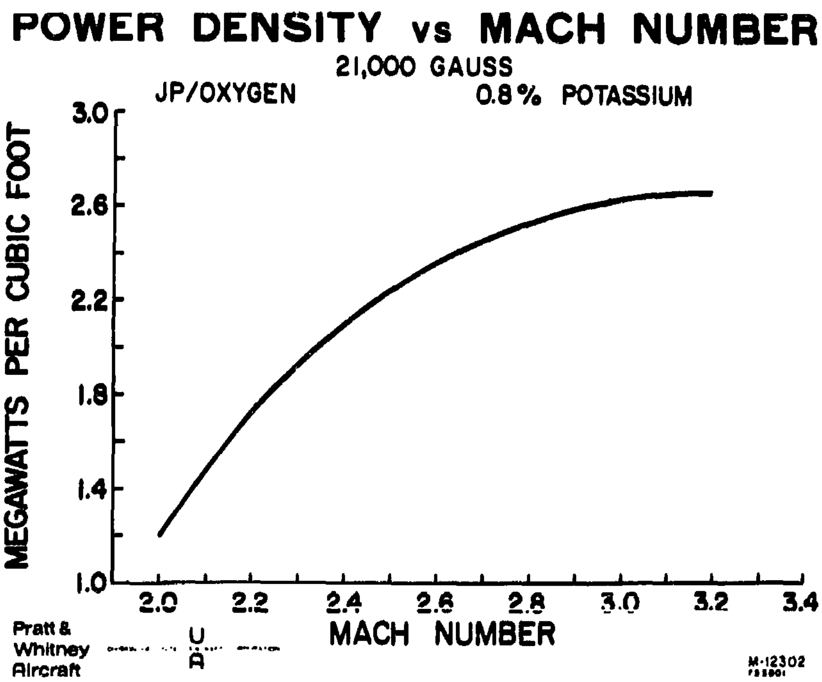
POWER DENSITY vs MACH NUMBER
21,000 GAUSS
JP/OXYGEN
0.8% POTASSIUM
MEGAWATTS PER CUBIC FOOT
3.0
2.6
2.2
1.8
1.4
1.0
2.0
2.2
2.4
2.6
2.8
3.0
3.2
3.4
MACH NUMBER
Pratt & Whitney Aircraft
M-12302

Fig. 2.

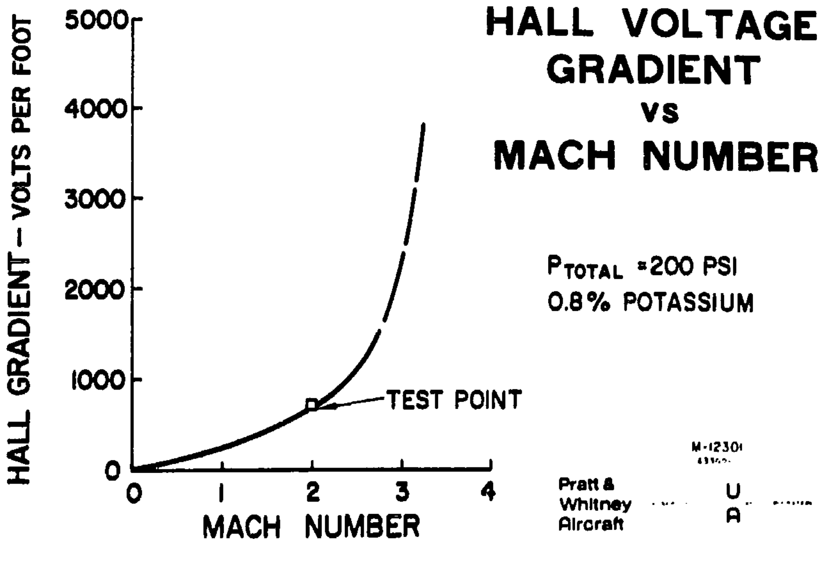
HALL VOLTAGE GRADIENT vs MACH NUMBER
HALL GRADIENT – VOLTS PER FOOT
5000
4000
3000
2000
1000
0
0
1
2
3
4
MACH NUMBER
TEST POINT
P_{TOTAL} =200 PSI
0.8% POTASSIUM
M-12301
Pratt & Whitney Aircraft
U
A

Fig. 3.

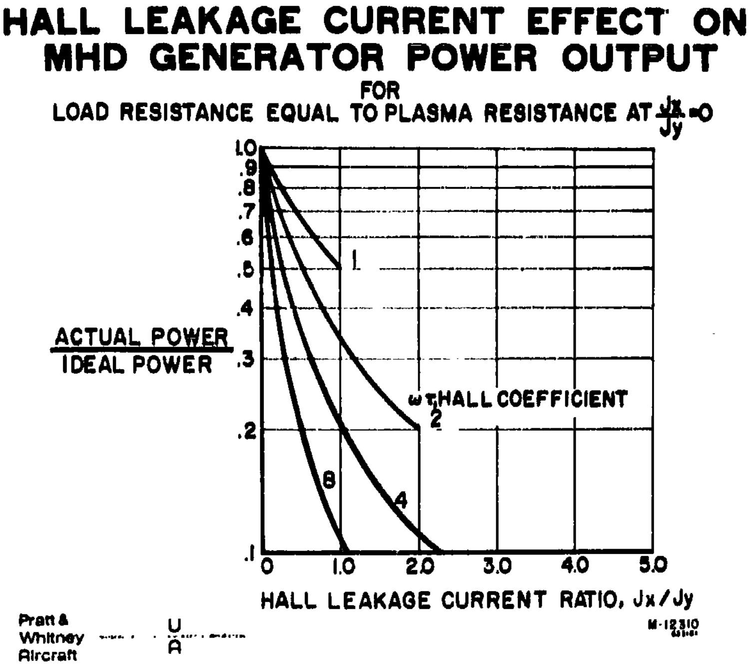
HALL LEAKAGE CURRENT EFFECT ON MHD GENERATOR POWER OUTPUT
FOR
LOAD RESISTANCE EQUAL TO PLASMA RESISTANCE AT Jx/Jy =0
ACTUAL POWER / IDEAL POWER
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
1
2
4
8
ωτ HALL COEFFICIENT
0
1.0
2.0
3.0
4.0
5.0
HALL LEAKAGE CURRENT RATIO, Jx/Jy
M-12310
Pratt & Whitney Aircraft
U
A

Fig. 4.

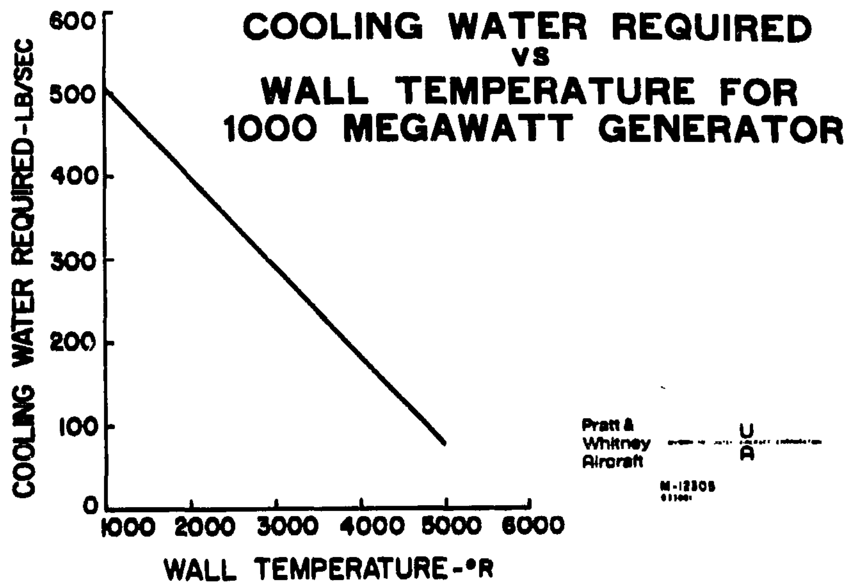
COOLING WATER REQUIRED
VS
WALL TEMPERATURE FOR
1000 MEGAWATT GENERATOR
COOLING WATER REQUIRED-LB/SEC
600
500
400
300
200
100
0
1000 2000 3000 4000 5000 6000
WALL TEMPERATURE-°R
Pratt &
Whitney
Aircraft
U
A
M-12305

Fig. 5.

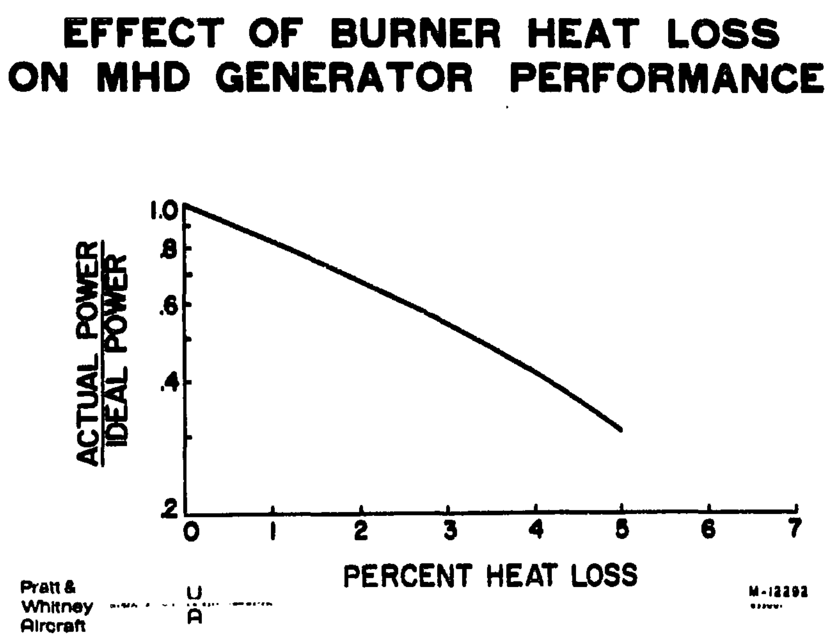
EFFECT OF BURNER HEAT LOSS
ON MHD GENERATOR PERFORMANCE
ACTUAL POWER
IDEAL POWER
1.0
.8
.6
.4
.2
0
1
2
3
4
5
6
7
PERCENT HEAT LOSS
Pratt &
Whitney
Aircraft
U
A
M-12292

Fig. 6.

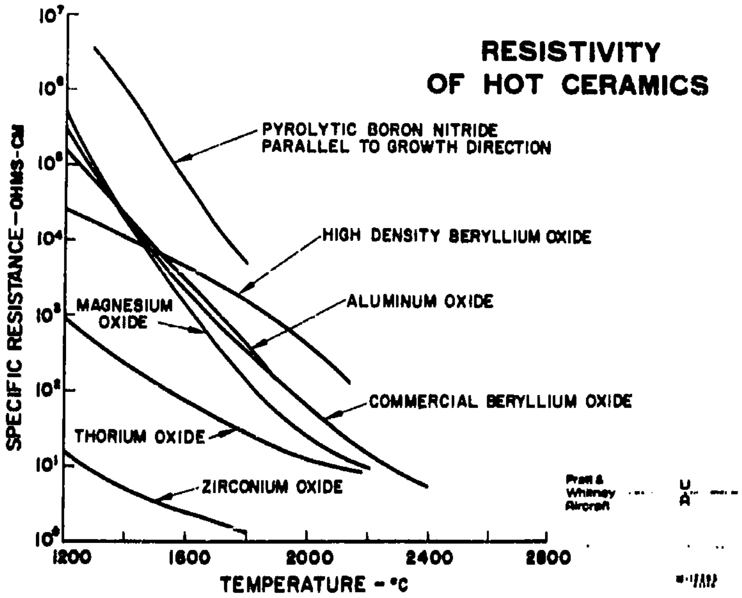

Fig. 7.

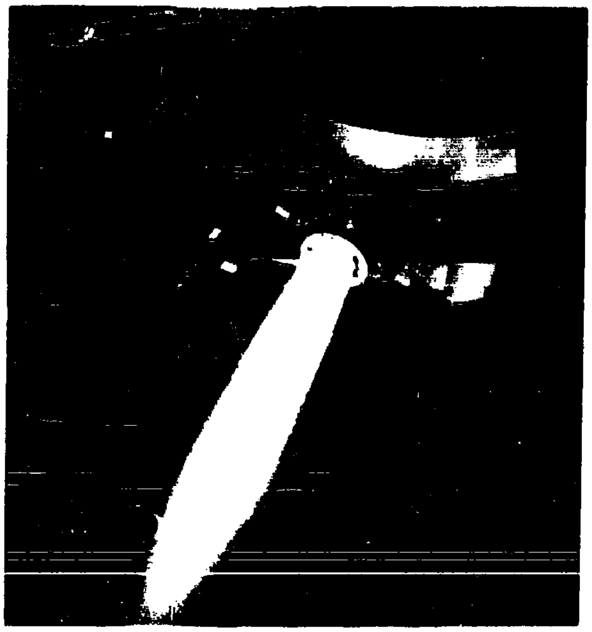

Fig. 8. Test stand

VERY HIGH POWER, LIMITED DUTY CYCLE,

ROCKET DRIVEN MHD GENERATORS

Arthur Kantrowitz
Thomas Brogan

Avco-Everett Research Laboratory

February 1, 1963

The largest utility central station steam-electric generating plants in operation in the United States today deliver an output of 500,000 kilowatts. Two such supercritical steam, double reheat units are located in the American Electric Power System, whose engineering subsidiary, the American Electric Power Service Corporation is associated with the Avco-Utility program for commercial development of the MHD concept. A unit of 1000 megawatts output is being built by the Consolidated Edison Company of New York. The thermal efficiency of these huge, modern steam electric units is approximately 40%. Thus, the heat input to the largest steam electric generating units now in operation is about 1250 megawatts, while units with heat inputs up to 2500 megawatts are being built. The installed cost for such units varies with locale and fuel that is fired, but approximates $125/kilowatt. The equipment is expected to run continuously and reliably for many years.

The total installed electric generating capacity in the United States today is approximately 100,000,000 kilowatts, a figure which is doubling every ten years. A single ten million kilowatt (10^{10}watt) unit would represent roughly 10 percent of the total electric generating capacity of the United States, and would cost over one billion dollars. In point of fact, of course, it is unlikely that such a unit would be built at this time because the country's electrical load is not sufficiently concentrated to make such a unit economically attractive.

In the combustion chamber of a single Atlas booster engine, the rate of heat release is equivalent to 2700 megawatts (2.7×10^9watts), or approximately the heat input to the very largest steam electric plant now under construction, and of two of the largest units now in actual operation. The size, weight, and cost of the Atlas engine are very small in comparison with that of the steam generator in an electric generating station of the same

heat input. With the use of an MHD generator the heat released in the combustion chamber of the Atlas rocket engine can be converted to electric power at an efficiency approaching that of the complete utility plant, while at the same time preserving the same advantages in weight, cost, and size for the whole generating system that the Atlas had over the steam generator. An MHD generator coupled to this Atlas rocket or its equivalent could deliver two minute bursts of power at a level of about 600-700 megawatts.

But engines of much greater size than the Atlas booster units are under development. The F-1 engine, for the NASA Saturn vehicle has a thrust of 1,500,000 pounds, and a heat release of 27,000 megawatts. Clusters of these F-1 engines are to be used for various Saturn configurations. These engines have been development fired on many occasions and the technology for handling them on the ground, and for supplying them with fuel and oxidizer for several minutes is well developed. The flight weight auxiliary hardware is also under development and two flights of the Saturn C-1 have taken place using a cluster of the Atlas booster engines mentioned previously and some of this development hardware.

A cluster of two F-1 engines, or their equivalent, when coupled to an MHD generator, is, we believe, capable of supplying two minute bursts at an average power level of ten million kilowatts (10^{10} watts) at an installed cost of approximately $3/kilowatt. The technology of combustion, fuel handling, site logistics, and operating equipment at the level required is in hand and under extensive development in connection with other programs.

What about the MHD generator? Since April of 1962 under Contract AF 33(657)-8380 with the Aeronautical Systems Division of the Air Research and Development Command, United States Air Force, using funds provided by the Advanced Research Projects Agency of the Defense Department, the Avco-Everett Research Laboratory has been engaged in the design, construction and test of a 20,000 Kilowatt Prototype, Self Excited MHD generator for limited duty cycle military and space applications. The specific purpose of this program is to demonstrate the feasibility of using more or less standard combustion heat sources to drive MHD generators of essentially unlimited output. The generator which is actually being built is not designed for any

specific application, rather, the objective has been to make the demonstration at minimum cost. It is felt that this program funded by the Advanced Research Projects Agency will provide very timely demonstration of the feasibility of generating bursts of several minutes at average powers up to one hundred million kilowatts. However, since the design is not directed to any specific application, modifications to the generator and additional work beyond the scope of the present program would be required to study in detail the application of this type of generator to a specific application. It is expected that initial operation of this generator will occur in late fall of this year.

In addition to the program presently underway and described above, the Avco-Everett Research Laboratory has for more than two years been operating a large (by present standards, at least) combustion driven MHD generator called the Mark II. A description of our work with this generator, which has delivered outputs as high as 1500 kilowatts will be presented at the forthcoming Engineering Symposium on Magnetohydrodynamics to be held at Berkeley, California April 10 and 11, 1963; a paper on the same subject is also being submitted to Physics of Fluids. The latter will shortly be available as an AERL Report. With the Mark II, it has been possible to get a precise understanding of the operation of MHD generators of the type we are concerned with here. The 20,000 kilowatt generator now being built is designed using the knowledge of generator fluid mechanics that was acquired in our work with the Mark II.

There is presently interest in the production of very high level pulses with a pulse width of several microseconds using an MHD generator and eventually explosive techniques. Personnel now of the Laboratory have studied such generators in the past. This work will be briefly reviewed in the presentation. We are unable at this time to see how to get to energy levels of 10^{10} joules in repeated microsecond pulses with such a technique. This would require a generator designed for impractically high instantaneous outputs. In addition, it would be necessary to operate at reasonable efficiency using typical gun pressures; this does not appear feasible in an MHD generator. Finally, the problem of providing a repetition rate of 1 cps with a charge of roughly 30,000# per shot (10% efficiency) appears staggering. A short synopsis of a thesis work in the area of shock tube MHD generators, carried out in 1956 is appended to this report.

Extrapolation to Large Size

The scaling laws inherently favor the use of large MHD generators. As previously mentioned, we believe the 10,000 MW unit could be built for a cost of about \$3/KW installed. Using a copper coil the generator would weigh between 400 and 1500 tons, depending on the amount of field dissipation that would be tolerated. If field dissipations of up to 10% of the gross output of the generator could be used it is conceivable that the weight could be reduced to the vicinity of 100 tons, approximately the same as that for a superconducting magnet operating at 10,000 amperes/cm^2. These remarks apply to the case of MHD generators driven by combustion gases and particularly, to typical rocket propellants.

The possibility of a nuclear reactor system using hydrogen, such as a Rover type system, should not be ignored. For comparable power outputs, assuming a gas temperature of 2500°K, the volume of the nuclear generator would be roughly an order of magnitude less than that of the combustion generator. One might expect that the weight would be reduced by a similar factor. If this could be accomplished, it is likely that generators of capacities up to 10,000 MW would be flyable.

We have indicated that we would expect that a 10,000 MW MHD generator would have an installed cost of \$3/KW. Of this cost roughly two-thirds or \$20 million is represented by equipment which is already in existence today. The \$20 million figure in fact represents the cost of a test stand for simultaneous testing of two F-1 engines, and so has the correct capability for our use. The \$20 million figure includes the two F-1 engines themselves, the stand, instrumentation, field and oxidizer storage, pumps, water cooling, and exhaust facilities. Thus the \$30 million figure leaves a cost of \$10 million for the 10,000 MW MHD generator itself. Now, our experience with much smaller generators is that the installed cost of the copper approximates \$2/lb. Assuming a coil weight of 3 million lbs. gives a total of \$6 million for the generator magnet if there is no improvement in cost/unit weight. There is thus every reason to expect that the \$3/KW installed figure can be met or closely approached in actual practice.

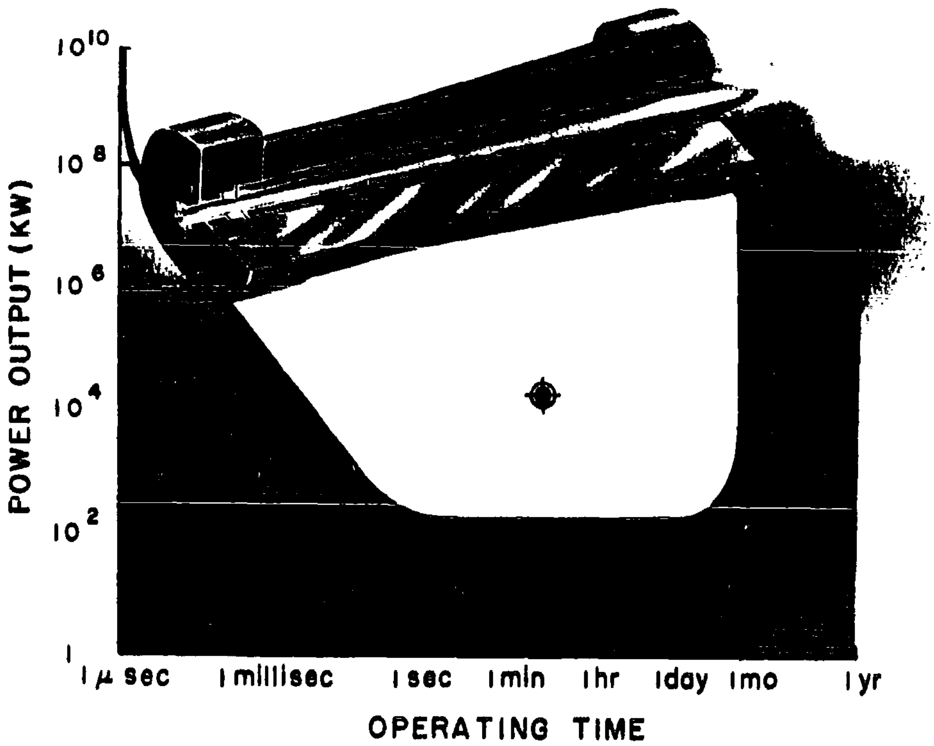

Fig. 1 Figure 1 shows the approximate range of power output and operating time that one might feasibly obtain with existing energy conversion and storage systems. Supplies that deliver power levels in excess of one megawatt for periods of one second to one day at a reasonable cost are notably absent from the open area of the graph. The existence of a few bulky and costly brute force systems in this range, presently used only in laboratory work, might be taken as an indication of future needs outside the laboratory. The importance of this high-power short-time range seems emphasized by the advent of pulsed communication, radar, and ECM equipment, and by the fact that modern methods of warfare make one day or even one minute a very long period of time. It is in this range that MHD generators can make an important contribution. For these reasons, the Avco-Everett Research Laboratory has under construction a prototype rocket-driven generator with output-time characteristics indicated by the symbol at 20 MW and 3 minutes. It is felt that this prototype will demonstrate the capability to generate power anywhere in the region not now covered by other sources. This work is being carried out under Contract AF 33(657)-8380 using funds supplied by the Advanced Research Projects Agency. Initial operation of this generator is expected in the fall of 1963.

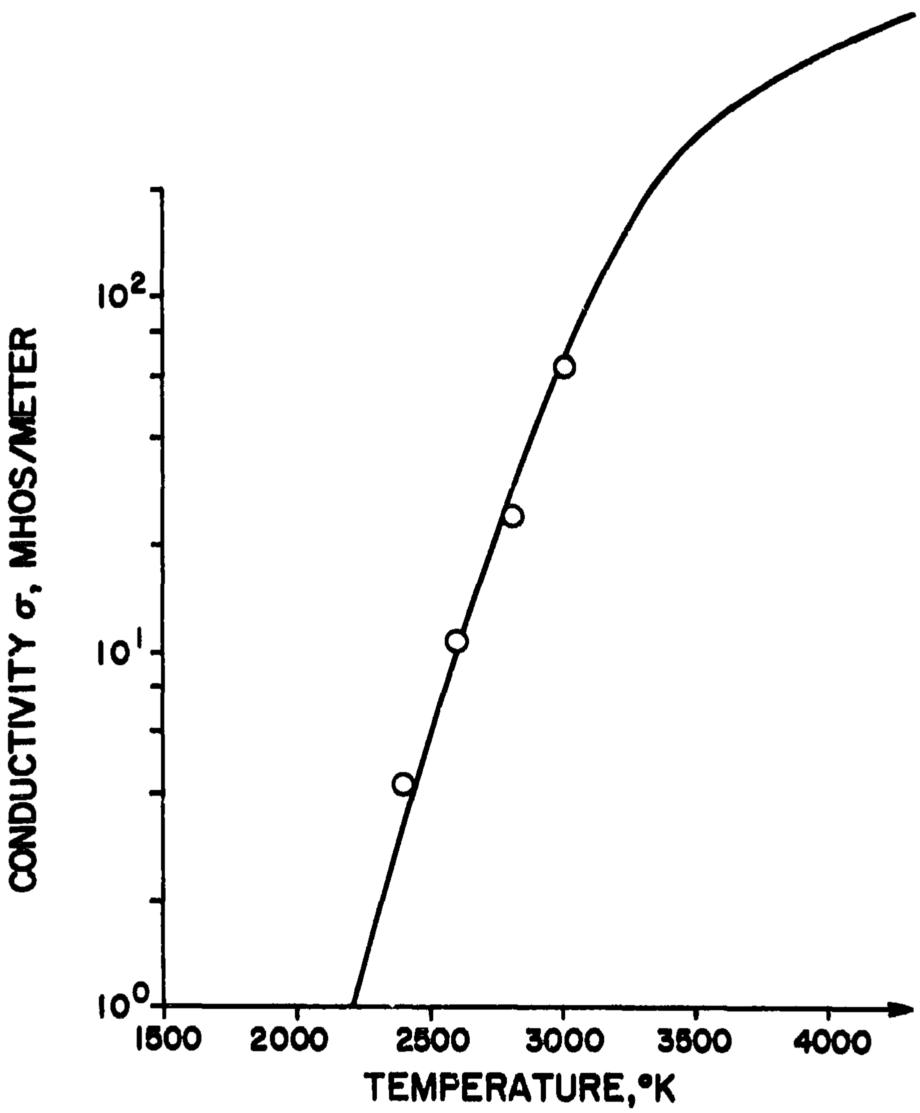

Fig. 2 At AERL and elsewhere, measurements have established the fact that the conductivity of combustion products seeded with potassium salts is adequate for use in an MHD generator. The results of the AERL measurements with JP4-O_2 at one atmosphere seeded with potassium carbonate are compared with theoretical values in Fig. 2. The good agreement between theory and experiment is indicative of the fact that the electrical conductivity can be accurately predicted.

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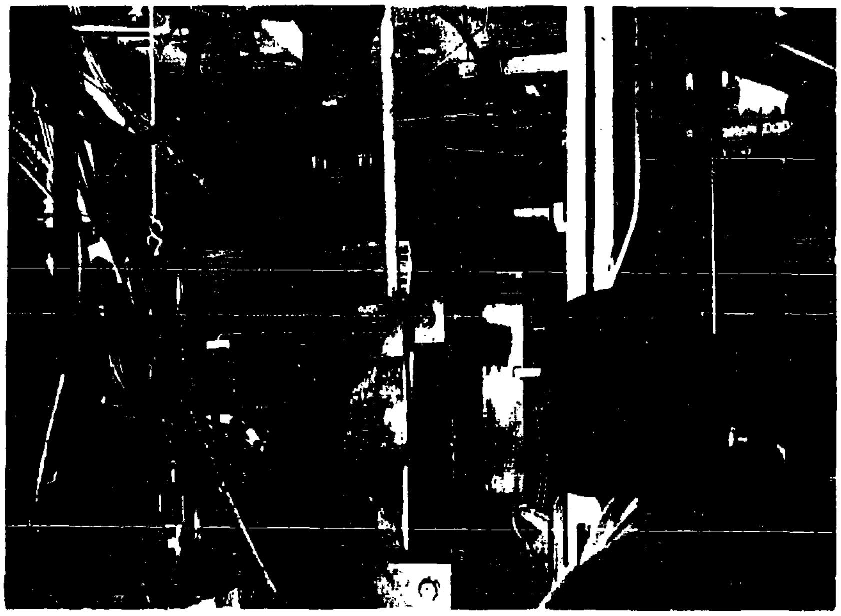


Fig. 3 AERL's 1.5 megawatt experimental Mark II MHD power generator is viewed from the control room. The MHD channel is inside the magnet and is attached to the combustion chamber which is seen protruding from the hole in the magnet. Mass flows up to 6.5 pounds per second are burned in this combustion chamber. The large number of wires seen emerging from the hole in the magnet carry the power output from the segmented electrodes of the generator channel to the individual loads. The various hoses carry fuel, oxidizer, and cooling water to the combustion chamber. The tubes above the burner carry pressure measurements to the instrumentation. The magnet is composed of sheets of copper connected in series; fields up to 33,000 gauss can be achieved. The structural steel about the magnet is used to contain the magnetic stresses that are produced when the magnet is operated.

With the Mark II generator, outputs of up to 1480 kilowatts have been produced. More importantly, experiments with this equipment have allowed us to obtain a detailed understanding of the flow in MHD generators. The success of the experiment has been due to the fact that it was built of sufficient size to permit the MHD effects to dominate the influences of friction, heat transfer and electrode drop. This machine has produced a measured "turbine efficiency" of 46% thru a stagnation pressure ratio of three at its maximum output; this is sufficient to guarantee that "turbine" efficiencies of above 80% can be achieved in large generators. The equipment is presently being modified for operation at a Hall coefficient of 5. Successful operation at a Hall coefficient at 2.5 - 3.0 has been achieved.

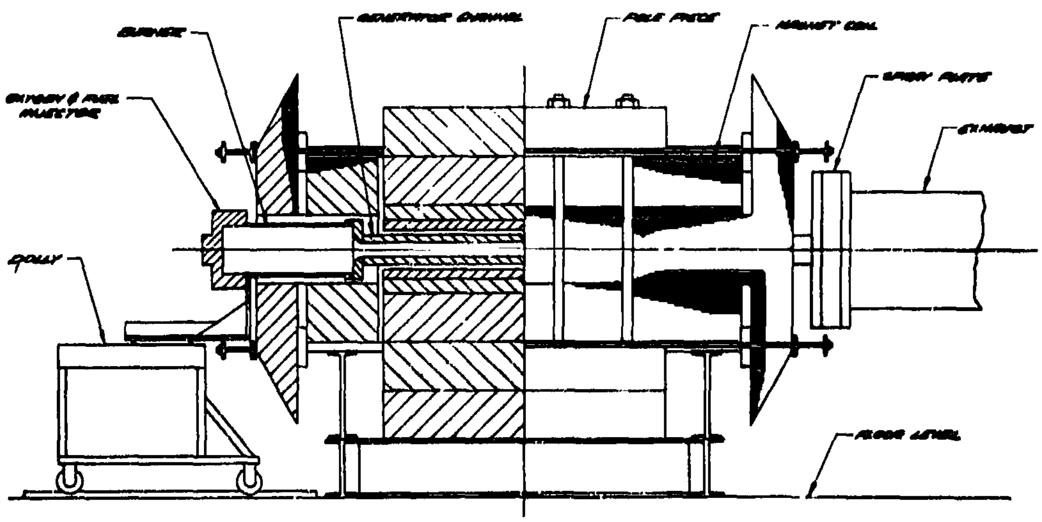
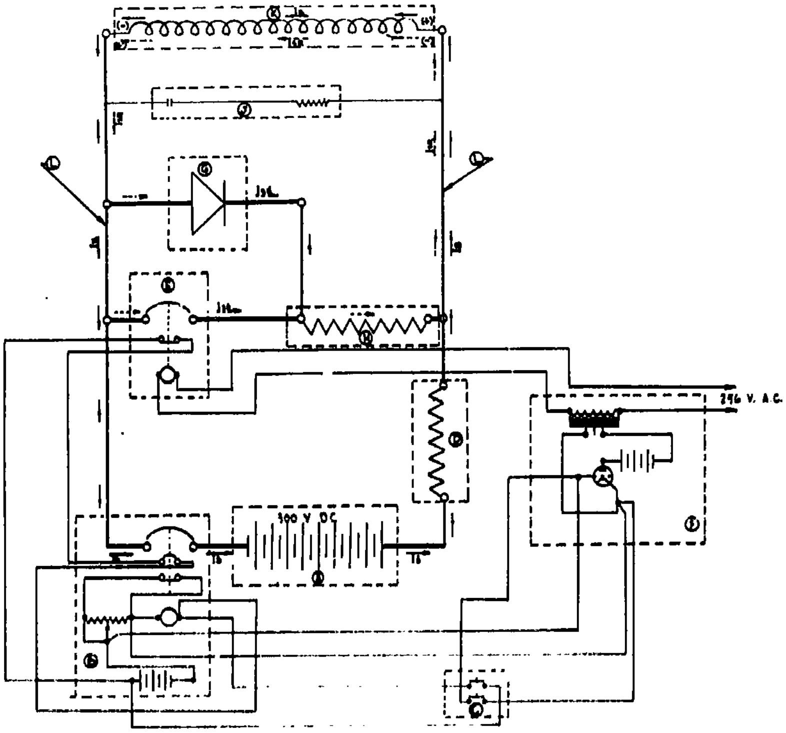


Fig. 4 Longitudinal section of the Mark II experimental MHD Generator. The channel and burner are removed from the upstream end of the magnet. In larger generators such as the 20 megawatt Mark V now under construction, for the Advanced Research Projects Agency, the magnet will diverge in the downstream direction to accommodate the change in channel area which comes about due to the generator pressure ratio. Thus for these large generators, the burner and channel are removed from opposite ends of the magnet. In larger generators also, the pole pieces made of iron would not be required; in large sizes, the dissipation in an air core field coil can represent only a small percentage of the output.



NOTES:

(A) D-C BATTERY POWER SUPPLY
(B) D-C CIRCUIT BRK & ITS COMPONENTS
(C) PUSH BUTTON STATION FOR CONTROL OF CIR BRK & SHORTING CONTACTOR (E)
(D) WATER COOLED CURRENT BALLAST RESISTOR
(E) FIELD MAGNET SHORTING CONTACTOR
(F) CONTROL CIR FOR MANUAL & AUTOMATIC CLOSING OF SHORTING CONTACTOR (E) & OPENING OF CIR BRK. (B)
(G) FIELD DISCHARGE RECTIFIER (FREE WHEELING)
(H) MAGNET SHORTING RESISTOR
(J) R C RESONANCE CIRCUIT LIMITER
(K) FIELD MAGNET
(L) TRANSMISSION LINES
I_B CURRENT FLOW OF BATTERY POWER SUPPLY (A)
I_{SR} SHORT CIRCUIT & FORWARD CURRENT FLOW OF RECTIFIER & SHORTING CONTACTOR (E) CIR.
(+) (-) POLARITY OF MAGNET WHEN D-C POWER IS APPLIED
(+) (-) POLARITY OF MAGNET WHEN D-C POWER IS REMOVED & MAGNET BECOMES AN ENERGY SOURCE

Fig. 5 Mark II magnet control circuit schematic. At peak field of 33,000 gauss, approximately six million joules are stored in the magnet field. The circuitry shown in the figure is designed to provide a discharge path for the energy when the magnet is turned off. The magnet in this case is driven by a battery bank with a peak output of 3300 kilowatts for one minute, rechargeable in an hour. The magnet of the Mark V, 20 megawatt generator under construction for ARPA will be driven by a portion of the generator output. For even larger generators, the magnet dissipation can be a small percentage of the total output.

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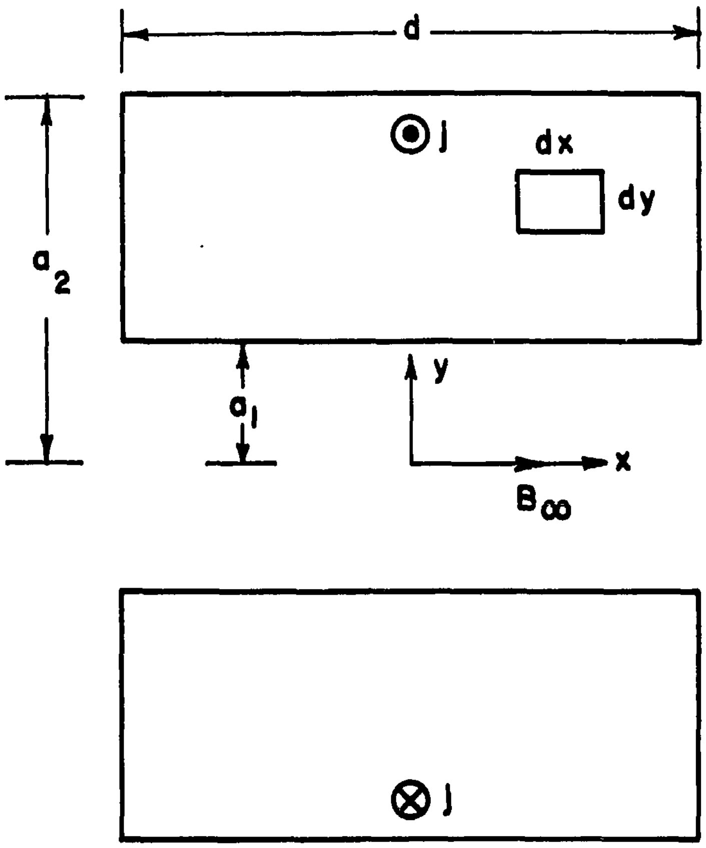

$$\frac{a_2}{a_1} = \alpha$$

$$\frac{d}{2a_1} = \beta$$

Fig. 6 Configuration for calculation of the magnet field due to infinite straight conductors and an air core. This configuration has been used for the construction of Mark II and Mark V magnets. It's chief advantage is simplicity. Power dissipation will exceed that of a magnet such as is shown in Fig. 8 for the same copper weight, but this is often outweighed by ease of construction and uniformity of the individual magnet turns. In generators of the limited duration variety, where weight is not determining, heat sink capacity often decides the coil weight in any case. For very large generators where magnet dissipation is unimportant, and where adequate heat sink capacity is provided by the shear size of the coil, the value of α may be reduced to near unity to reduce coil weight. The heat of vaporization of liquid oxygen, oxidizer can be used to maintain the coil at $90^{o}K$ and reduce dissipation. Again, this technique is useable only by generators with a large oxygen flow, and is chiefly useful to reduce weight.

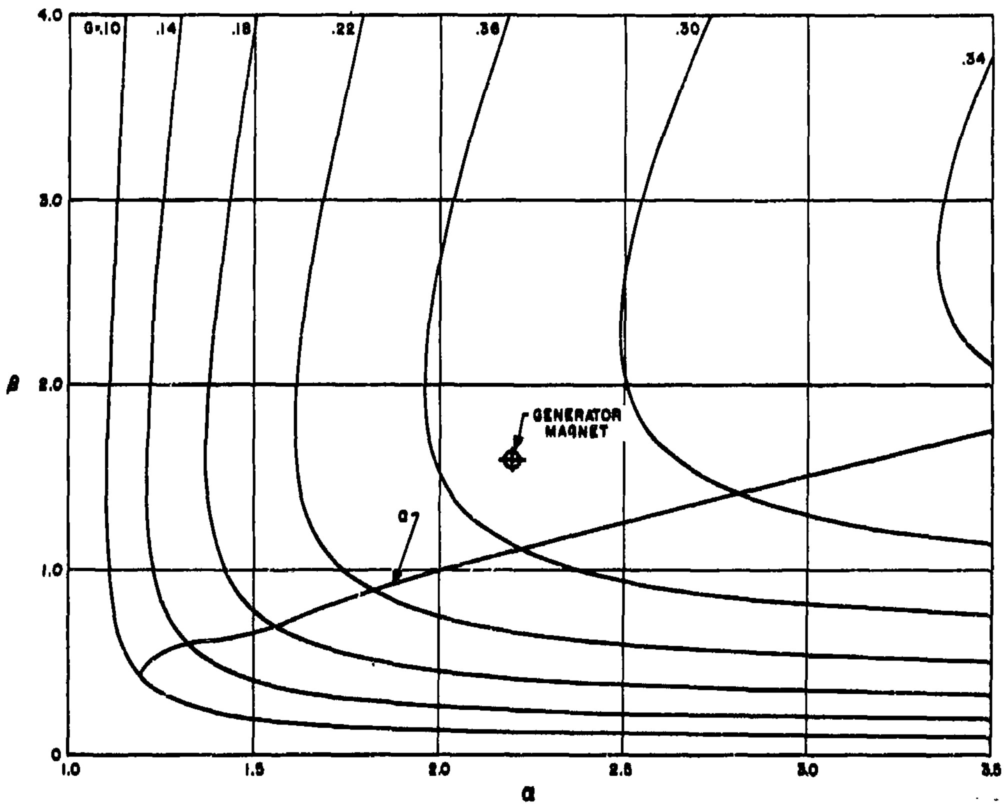

Fig. 7 G factors for the configuration of Fig. 6. Relationship between the various quantities is:

$$B = G\left(\frac{P\sigma\lambda}{\ell}\right)^{1/2}$$

where P is the power in watts, ℓ the length in centimeters, B the field in gauss, σ the conductivity of the coil material in mhos/centimeter, and λ is the packing factor. For very large generators, the trend would be to the lower values of α since dissipation is not important.

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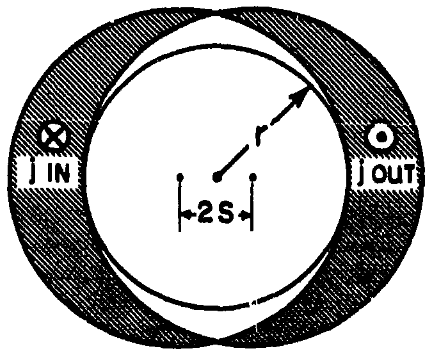

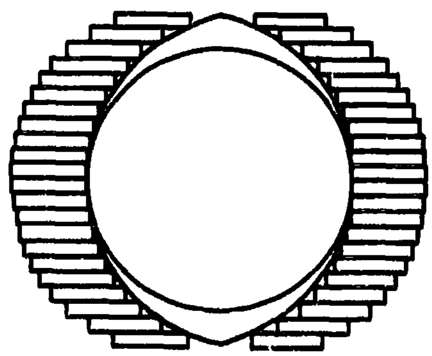

Fig. 8 Configuration of the so-called "crescent" coil geometry, a more efficient and lower weight construction than that shown in Fig. 6. The lower photo is an approximation to the top geometry and would be used in coils of practical construction. This geometry produces an identically constant magnetic field in the space between the overlapping circles.

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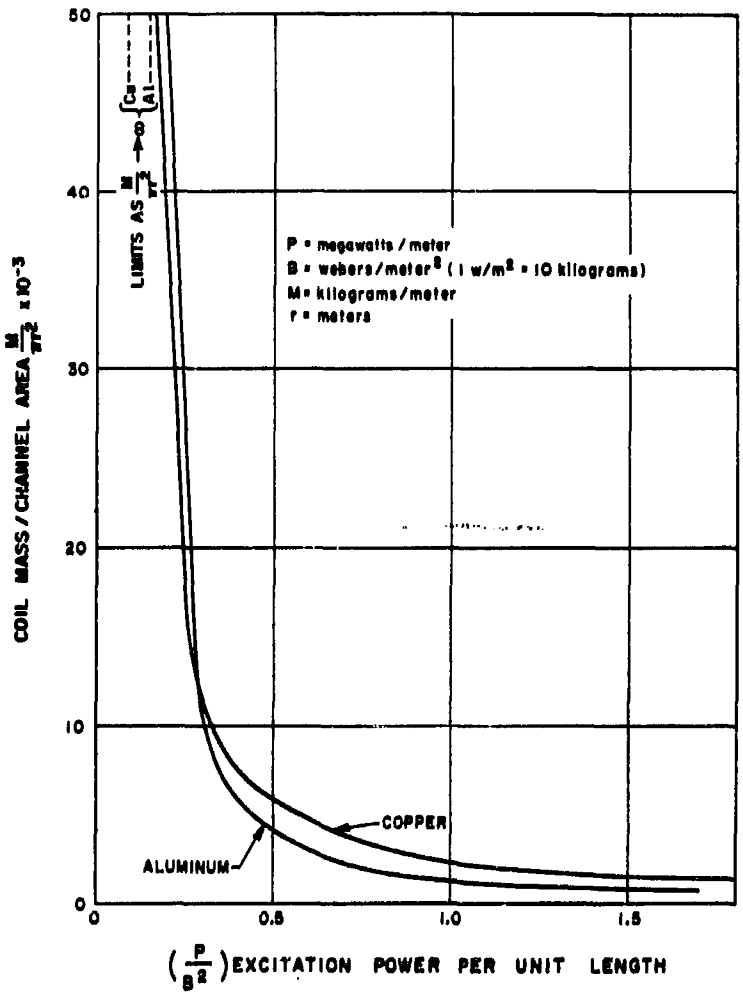

Fig. 9 Mass/unit length vs excitation power/unit length for an infinite crescent coil as shown in Fig. 8 with radius r. In large generators where the dissipation is not important, the trend would be to higher excitation powers/unit length and lower relative weight. For very large generators, modifications of the basic generator geometry such as a disk shape might well prove more economical and compact than the conventional geometry. Modifications of the curves of Figs. 7 and 9 are used in the design of superconducting magnets, where the current density cannot exceed a maximum value determined mainly but not completely by the local field and the particular material in question.

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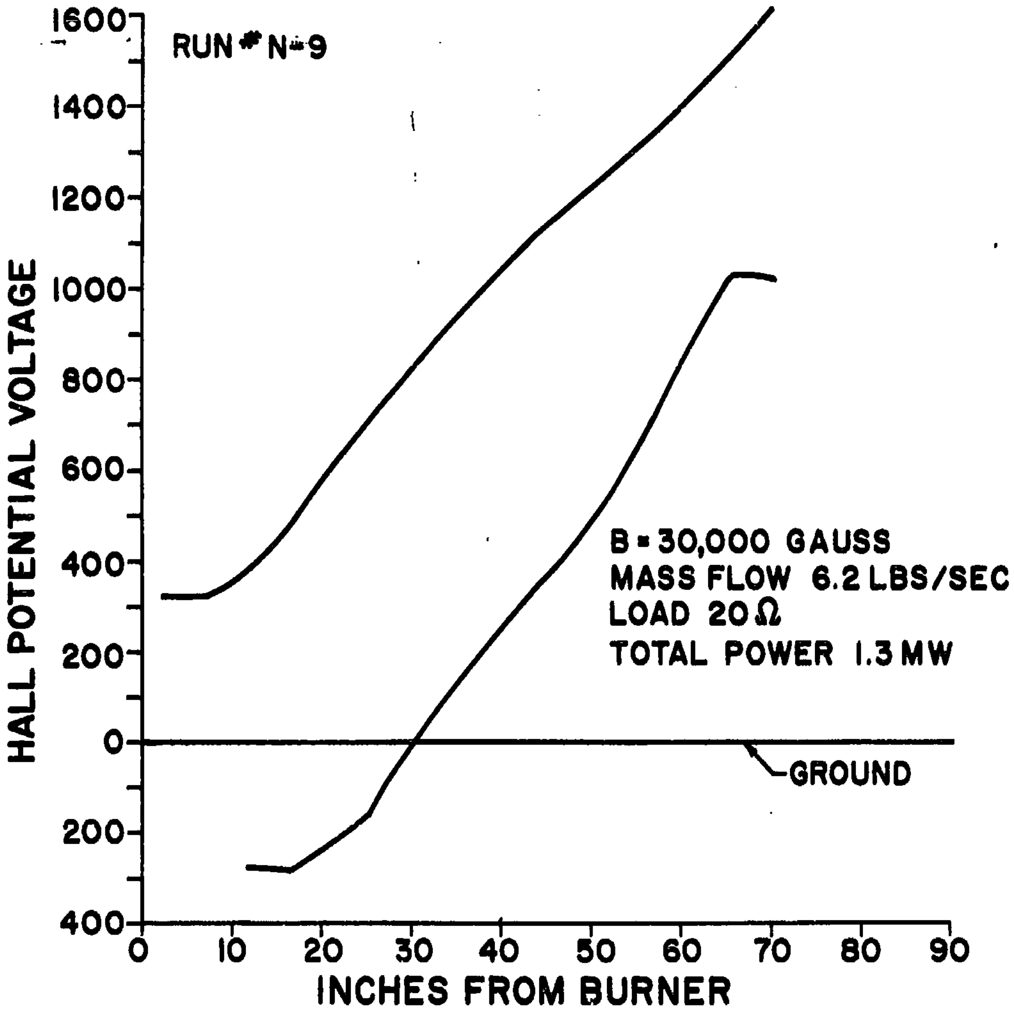

Fig. 10 Typical voltage distribution for the Mark II generator, in the case shown, the output is 1.3 megawatts, and the flow is supersonic. The axial field is due to the appearance of Hall effect; to prevent Hall current flow, segmented electrodes must be employed. For very large MHD generators connected to a single load, it would be possible to allow the Hall currents to flow without penalizing performance to a serious degree.

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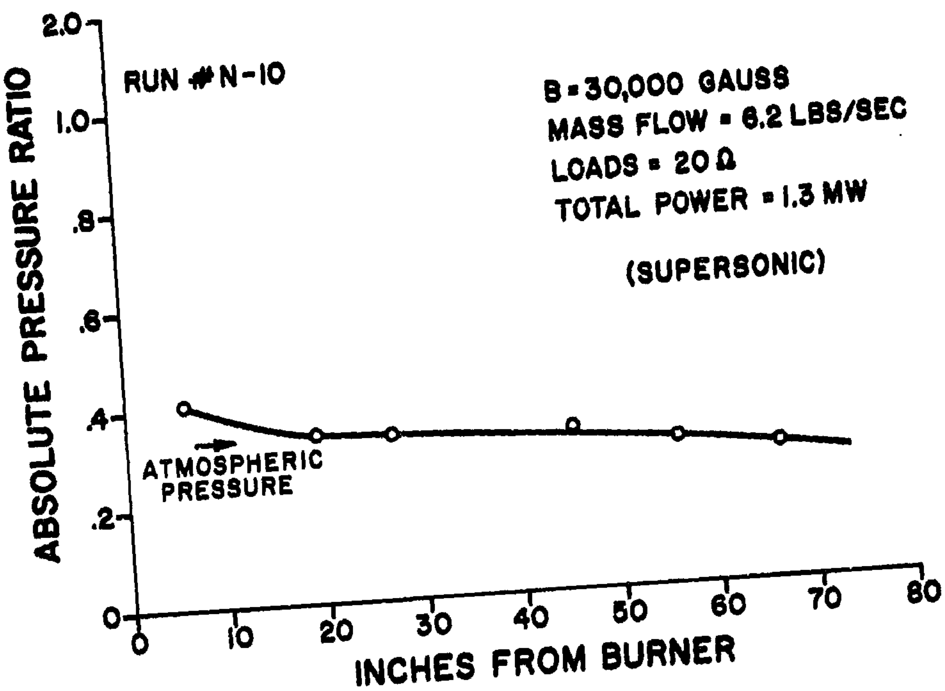

Fig. 11 Longitudinal pressure distribution for a supersonic run of the Mark II. Total power output, 1.3 megawatts. A diffuser is used on the generator exhaust to permit an atmosphere back pressure.

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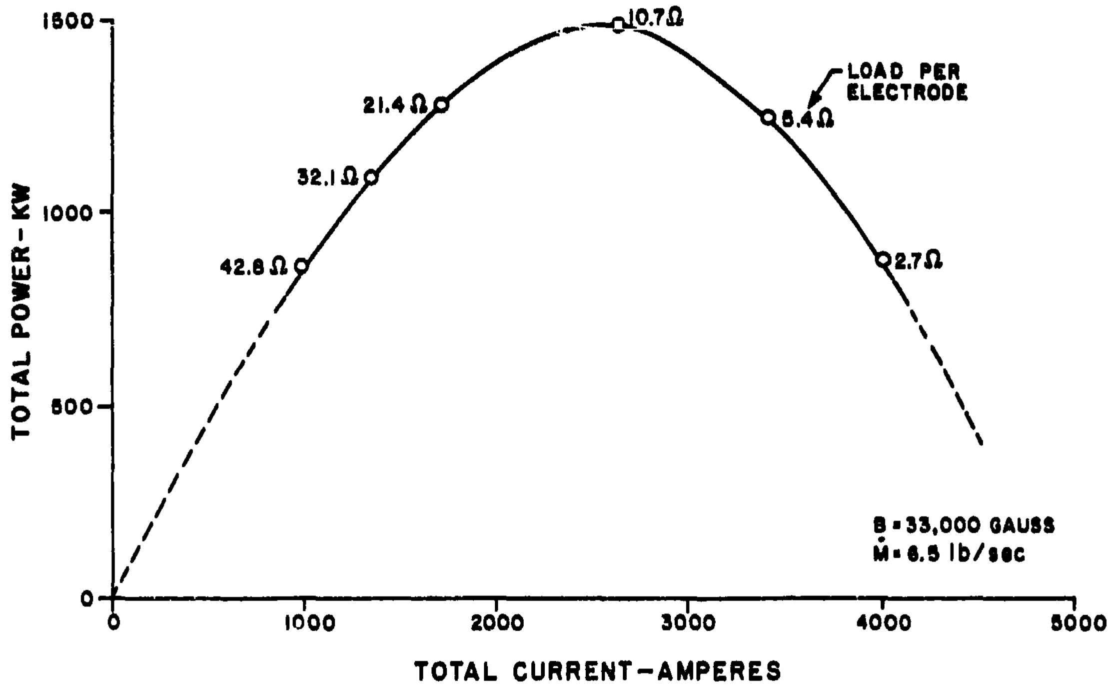

Fig. 12 Total power output vs total current for the Mark II generator using a channel with an area ratio of 2.5, a magnetic field of 33,000 gauss, and a mass flow of 6.5 pounds/second. The load per electrode is the value of resistance connected to each of the segmented electrodes and was uniform along the whole generator length. Better results could have been achieved with load variation along the length. The generator internal impedance at each electrode is approximately 5 ohms.

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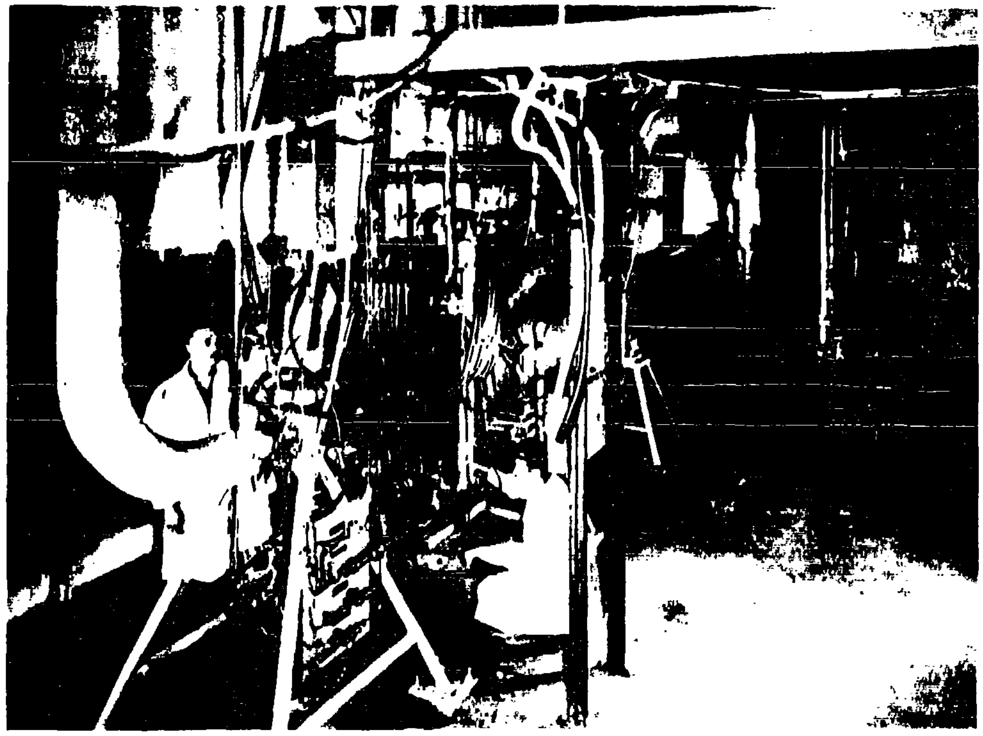

Fig. 13 One of two test cells of the Long Duration Test Facility at the Avco-Everett Research Laboratory. The Facility is used to test generator components at relatively low power levels and for very long periods of time. Mass flows up to three pounds per second are used. The oxidizer is nitrogen-oxygen mixtures of various ratios preheated to temperatures up to 1600° F; combustion pressures up to 150 psia may be employed. MHD generator walls have been operated for up to 140 hours in this cell, using commercial fuel oil with its attendant ash, and seed. A 18,000 gauss iron magnet is being installed in this cell, while a 40,000 gauss saddle shaped superconducting magnet with a 7" gap at room temperature is under construction for installation in the cell.

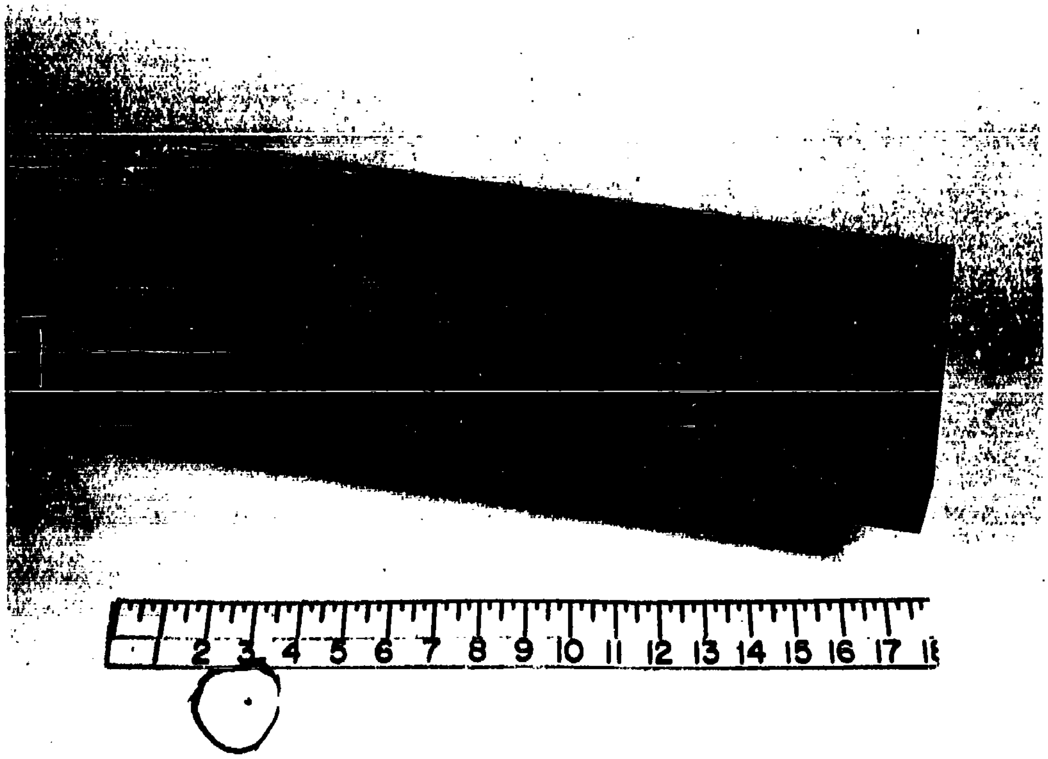

Fig. 14 Example of a water cooled peg wall for an MHD generator developed and tested at Avco-Everett Research Laboratory for periods up to 140 hours under conditions simulating those in an MHD generator. No special materials are required for this wall, since the operating temperatures are those of normal materials of construction. In addition, and of great importance for short duration burst MHD generators, this wall is highly resistant to thermal shock; normal operating procedure during tests at Avco-Everett Research Laboratory includes wide open starts and instant shutdowns. A wall of this type is used in the Mark V generator, while an uncooled version was used with the Mark II.

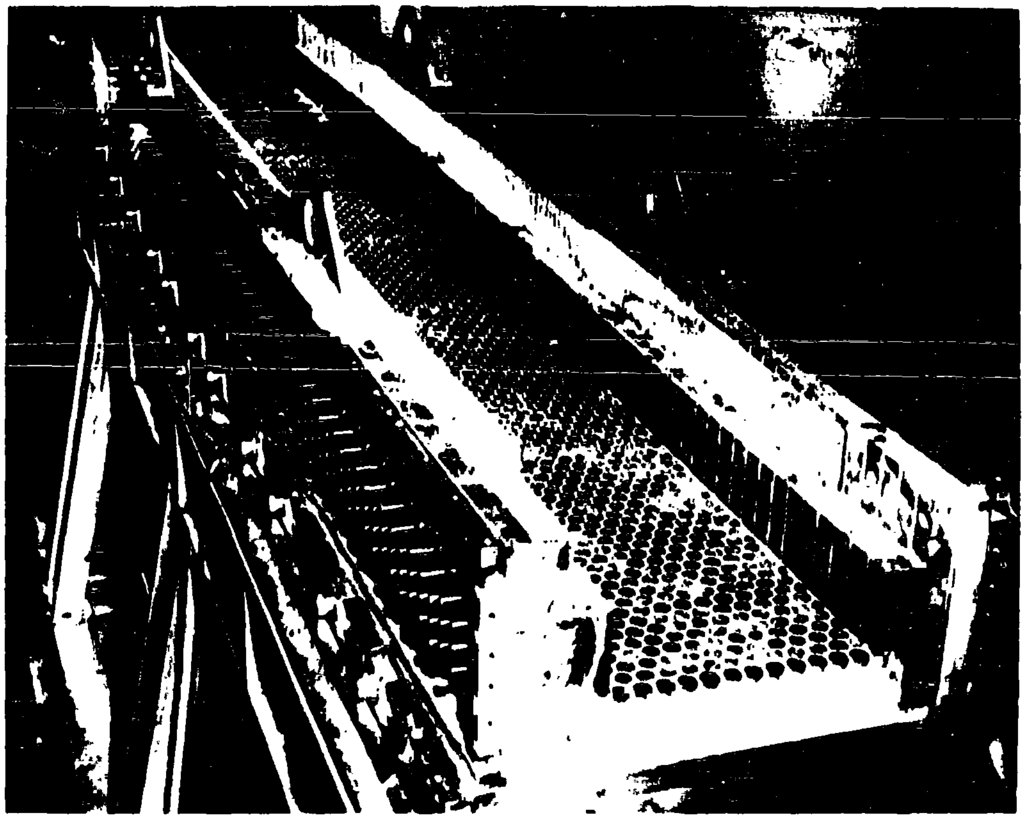

Fig. 15 View of the Mark II channel showing the heat sink peg wall and the segmented electrode wall. The peg wall has been operated over 250 times with wide open starts and instant shutdowns, and has withstood voltages as high as 150 volts per peg.

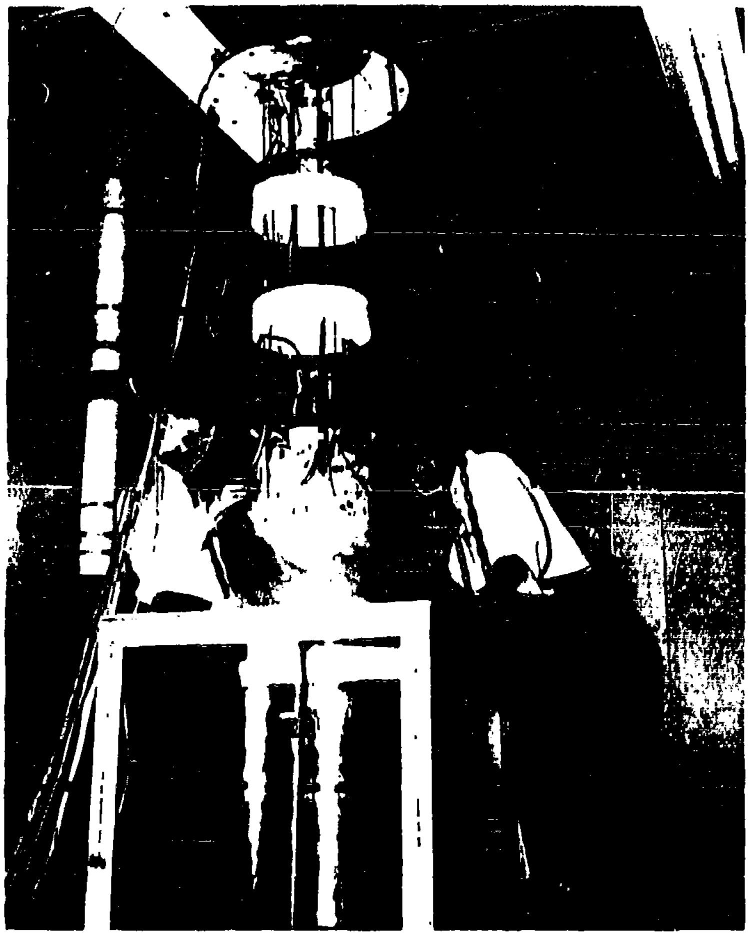

Fig. 16 Five-inch, 30,000 gauss superconducting solenoid is lifted from its container of liquid helium at Avco-Everett Research Laboratory. A seven-inch diameter saddle shaped superconducting magnet for field strengths of 40,000 gauss is under construction at Avco-Everett Research Laboratory and will be installed on the Long Duration Test Facility when it is completed in the spring.

Because of high cost, it seems unlikely at this time that superconducting magnets will find much application in ground based applications using MHD generators designed for relatively short bursts (minutes) at very high power level; the dissipation in a conventional magnet is small at high power level. For flight applications, however, the potential weight advantages of the superconductor may permit its use.

Fig. 17 Avco-Everett Research Laboratory's facility for the development of MHD generators. The facility is located on a 58 acre tract on the Merrimac River near Haverhill, Mass., and was completed last September. It is valued at one half million dollars. The Mark V, 20 megawatt MHD generator is under construction for the Advanced Research Projects Agency in the taller part of the structure. It should be mentioned that the test cell is considerably oversize for a generator of the Mark V capacity. The remainder of the building houses auxiliary equipment such as water pumps, fuel pumps, magnet pre-exciter, control room, offices and shop.

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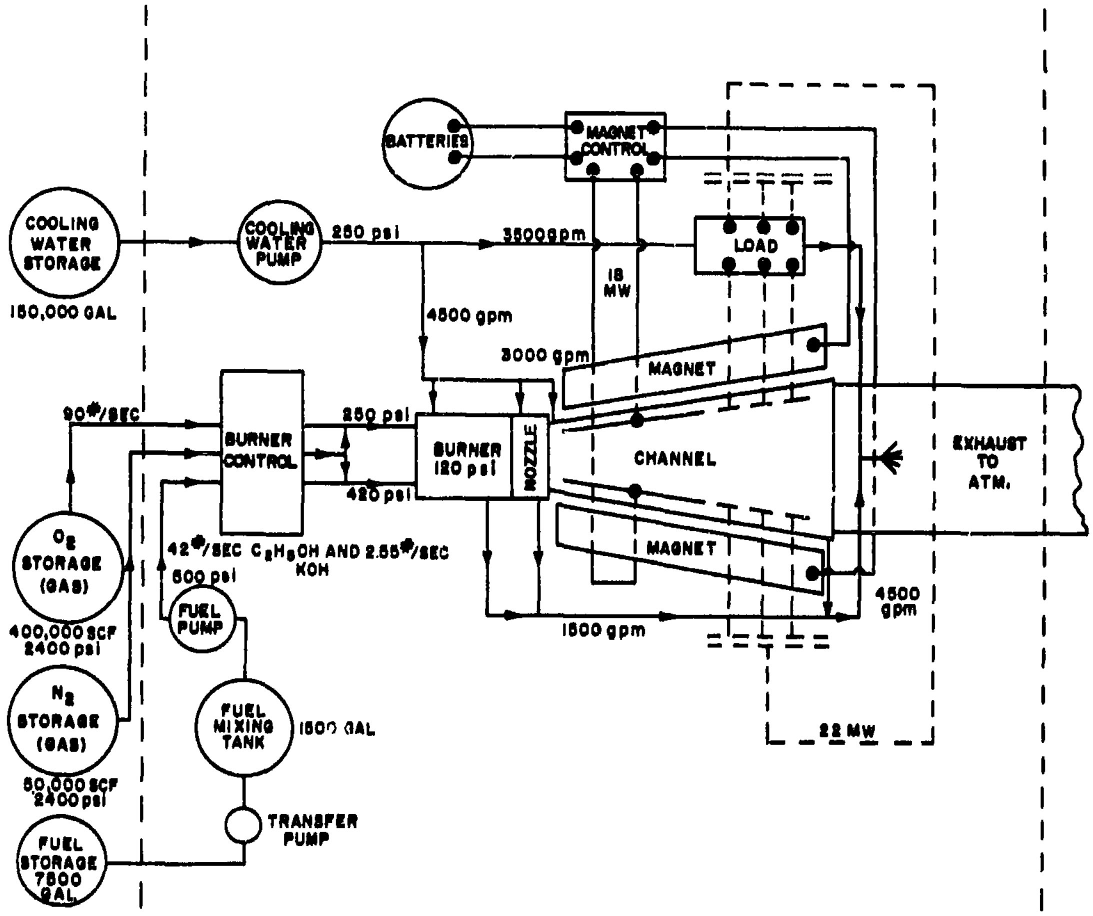

Fig. 18 General arrangement of equipment and systems for the Mark V generator. It should be borne in mind that the generator is a developmental item and that the various auxiliary components such as pumps have been selected with no thought to portability, independence from outside sources of power, compactness or weight. Low cost has been a prime factor in the choice of much of the equipment. It is certain that given the impetus of a specific application or goal, very considerable improvements could easily be achieved with regard to any of the items mentioned above. Design for overpressure is not likely to be a problem; the MHD generator; magnet and burner are all pressure vessels.

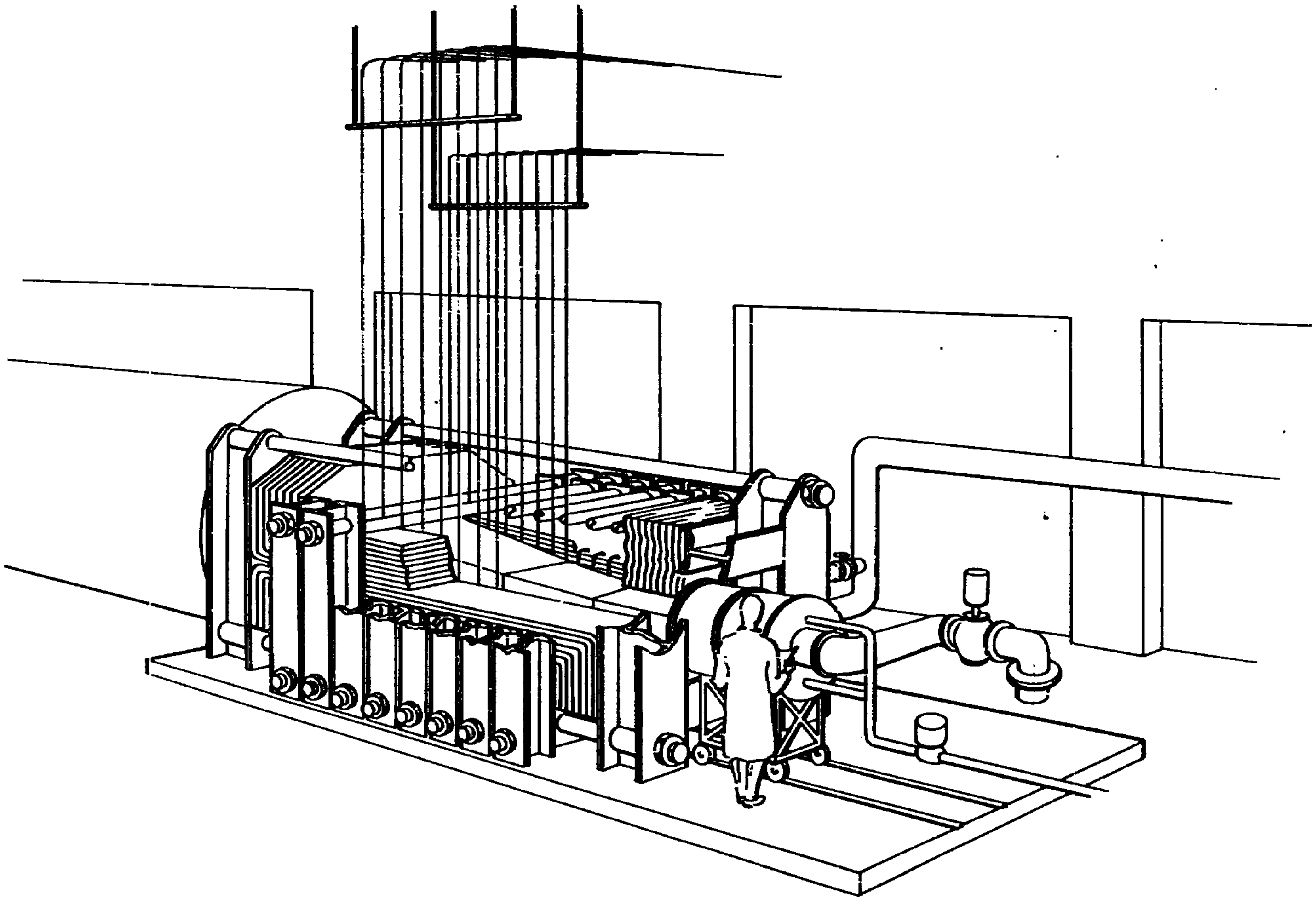

Fig. 19 Artists conception of the Mark V generator. Standard structural steel members have been used to contain the magnetic stresses at low cost but with very considerable weight penalty.

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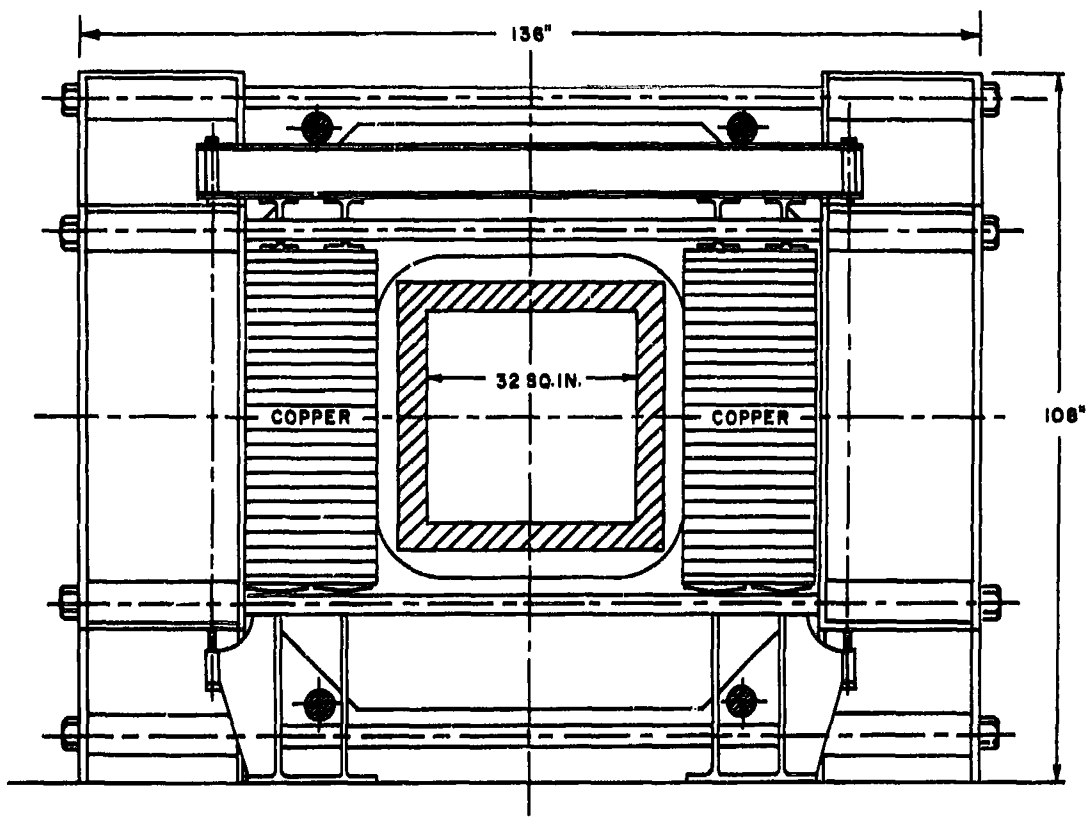

Fig. 20 Cross-Section of the copper and re-enforcement structure in the 20 megawatt Mark V MHD generator being built for ARPA under Contract AF 33(657)-8380. The coil is uncooled and absorbs about 18 megawatts of the generator output at full power. It is temperature rise in the coil which limits the generator operating time to three minutes; a cooled coil (water, liquid oxygen, superconductor) would permit indefinite operation assuming sufficient storage of combustables.

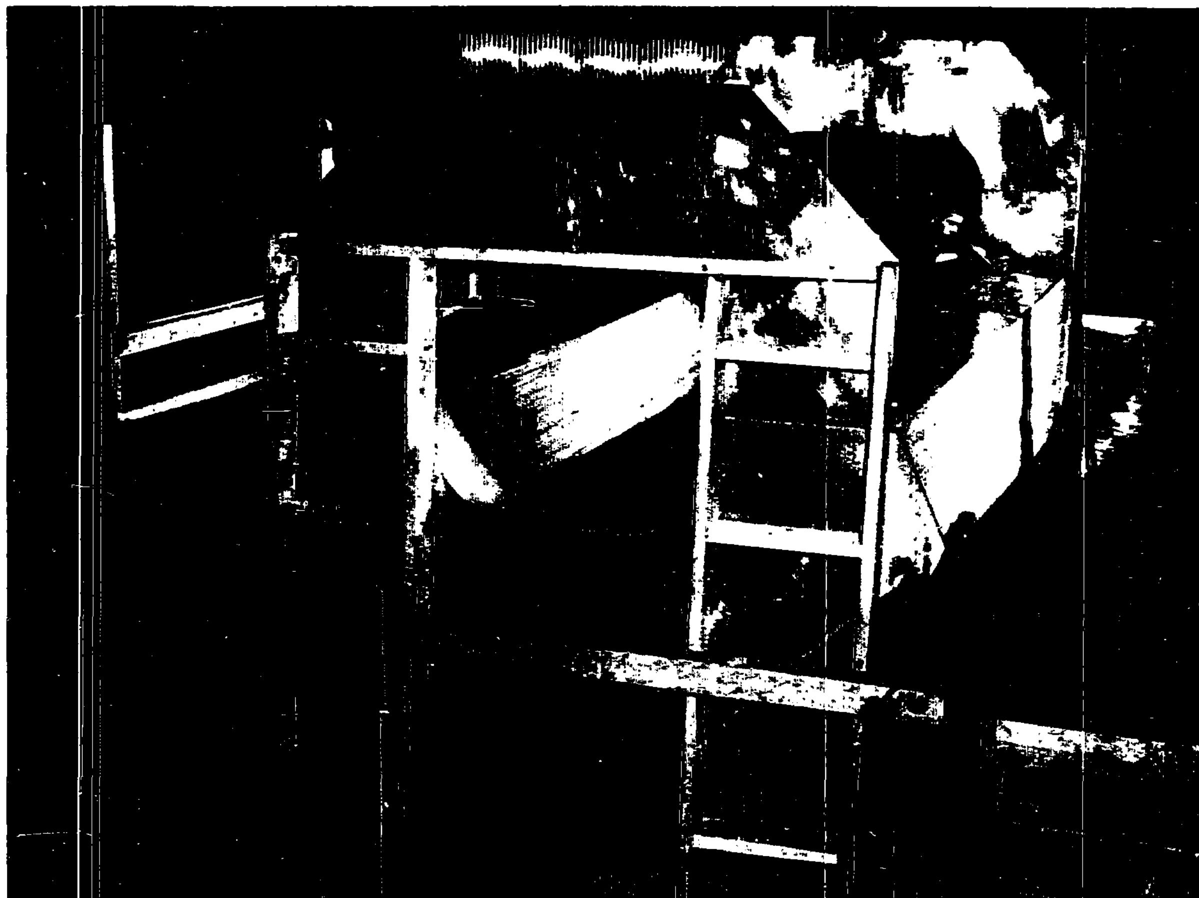

Fig. 21 Present status of erection of the Mark V field coil. Over half the turns have been installed. It is expected that the Mark V will be operated in the fall of this year.

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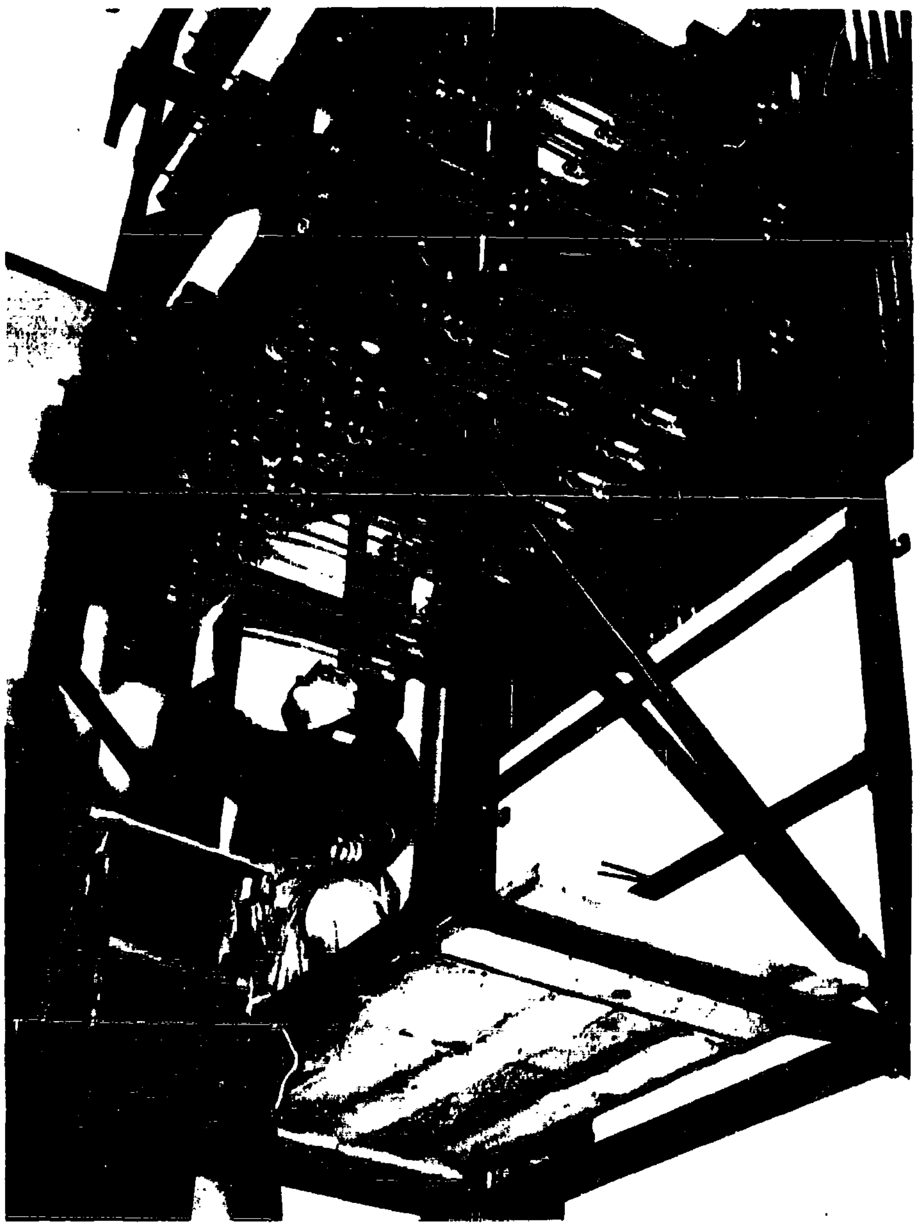

Fig. 22 Installation of the Mark V field coil shorting and discharge circuit. On shutdown, the rectifiers (one of which is being tightened in place by the technician) conduct and discharge the magnet.

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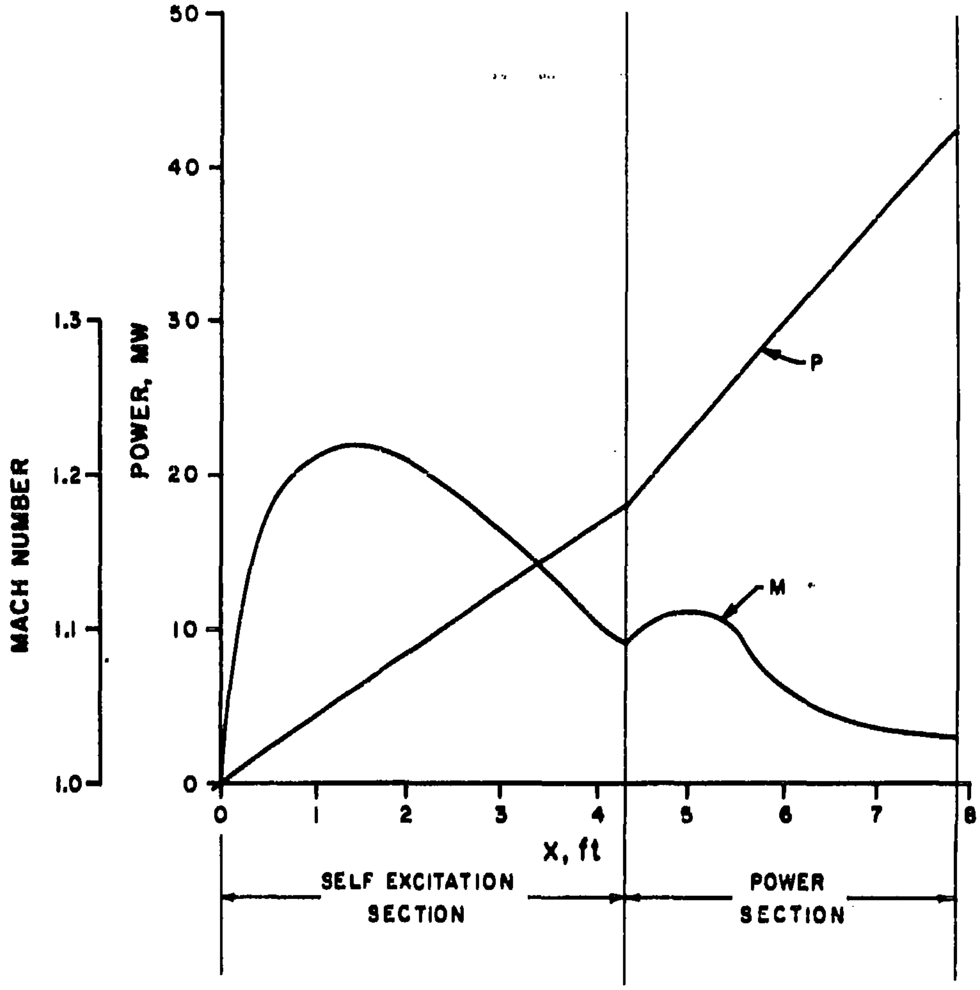

Fig. 23 Calculated power output and flow Mach Number vs distance along the channel in the Mark V generator. The power output from the self-excitation section is delivered to the magnet. The output from the segmented electrodes in the power section is delivered to water cooled adjustable ballast resistors. In a generator of larger size, the fraction of the gross output power consumed by the magnet would decrease roughly inversely proportional to the gross output given similar coil geometry. However, in larger sizes, increased dissipation would be desirable because it would be accompanied by reduced weight.

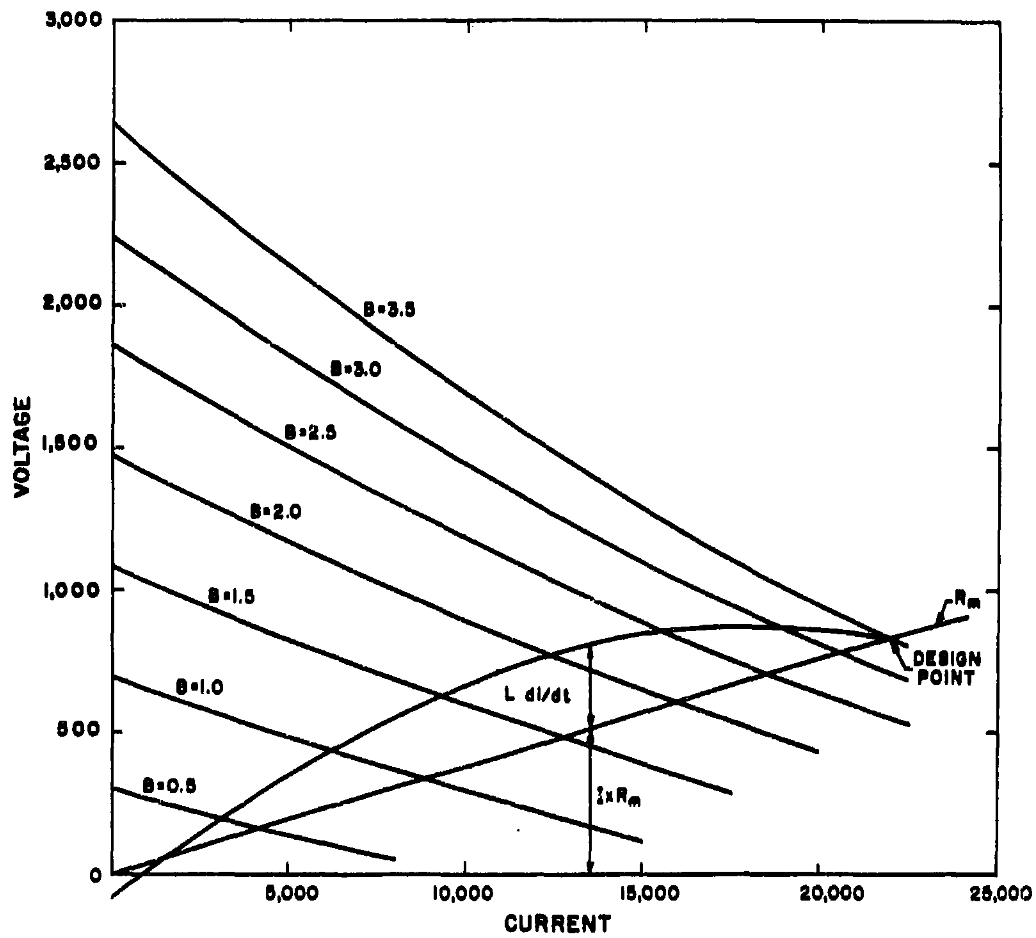

Fig. 24 Voltage-Current characteristics for the Self Excitation Section of the Mark V generator, at different values of magnetic field strength and design mass flow and seed concentration.

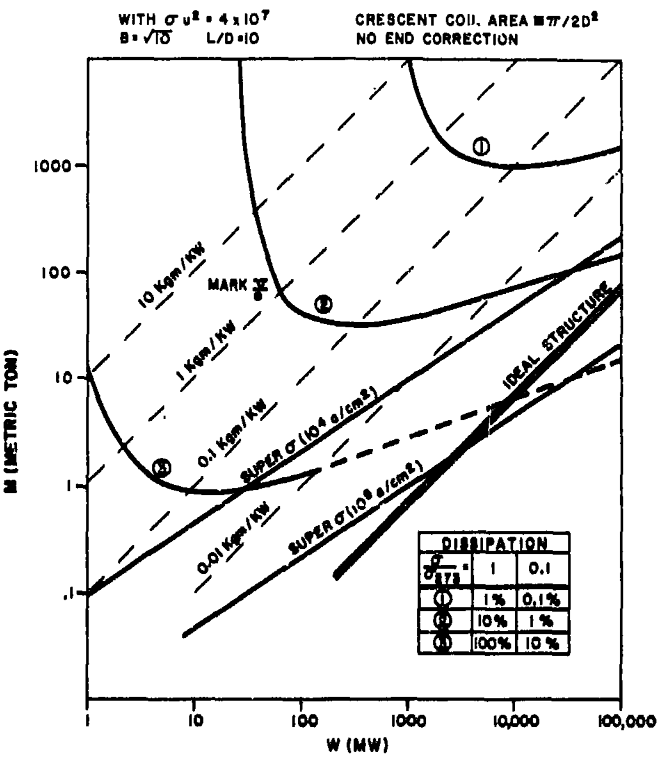

Fig. 25 Weight characteristics of a combustion product driven magnetohydrodynamic generator as a function of power output, coil dissipation, or current density in superconductor. Solid curves #1, 2, and 3 respectively apply to the case of field coils which consume 1, 10, or 100% of the MHD generator output if the coil is copper, at room temperature, or 1/10 of these percentages if the resistivity is reduced a factor of 10 by cryogenic cooling. Liquid oxygen cooling reduces the resistivity by a factor of approximately 5. The characteristic of the Mark V generator as designed is indicated. With the MK V, the coil dissipation is somewhat less than half of the gross output. With a room temperature coil the magnet weight would be between 100 and 1000 tons for 10 and 1% coil dissipation respectively. It is thus not improbable that such a generator could be transported on a prime mover or even flown.

The performance of the superconducting coil is dependent on the current density which can be taken by the superconductor. However, because of low packing factor and the need for protective circuitry in the form of additional metal, it is likely that the average current density will approximate the 10^4 amperes/cm^2, rather than the higher figure. To the weight of the coil material itself, in the case of the superconductor, must be added the weight of dewar and helium storage.

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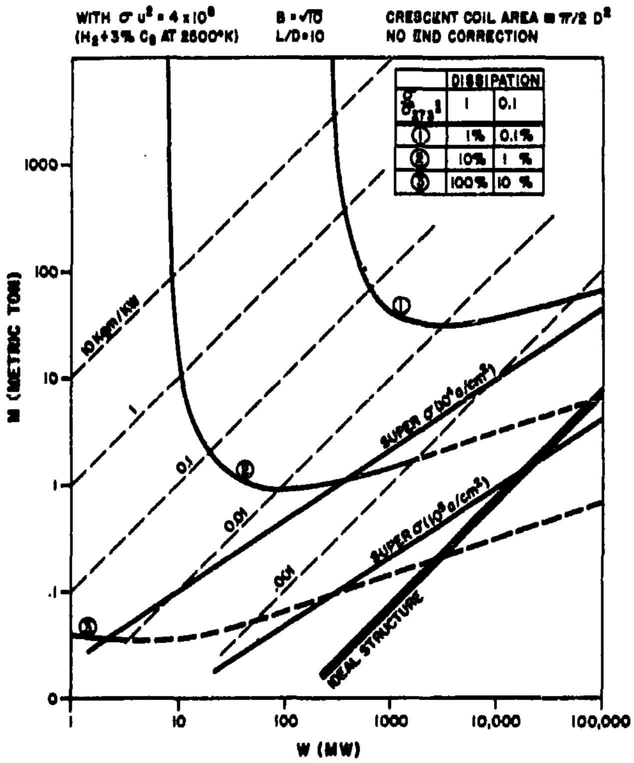

Fig. 26 The same results as portrayed in Fig. 25, except as applied to a generator using hydrogen gas at a temperature of 2500°K. This system would be used with a nuclear reactor of the Rover type and be designed for flight. Because the power density in this type of generator is increased by a factor of 10 over that of the combustion generator due to the improved electrical properties and higher gas velocity, there is significant weight reduction as compared with the combustion system.

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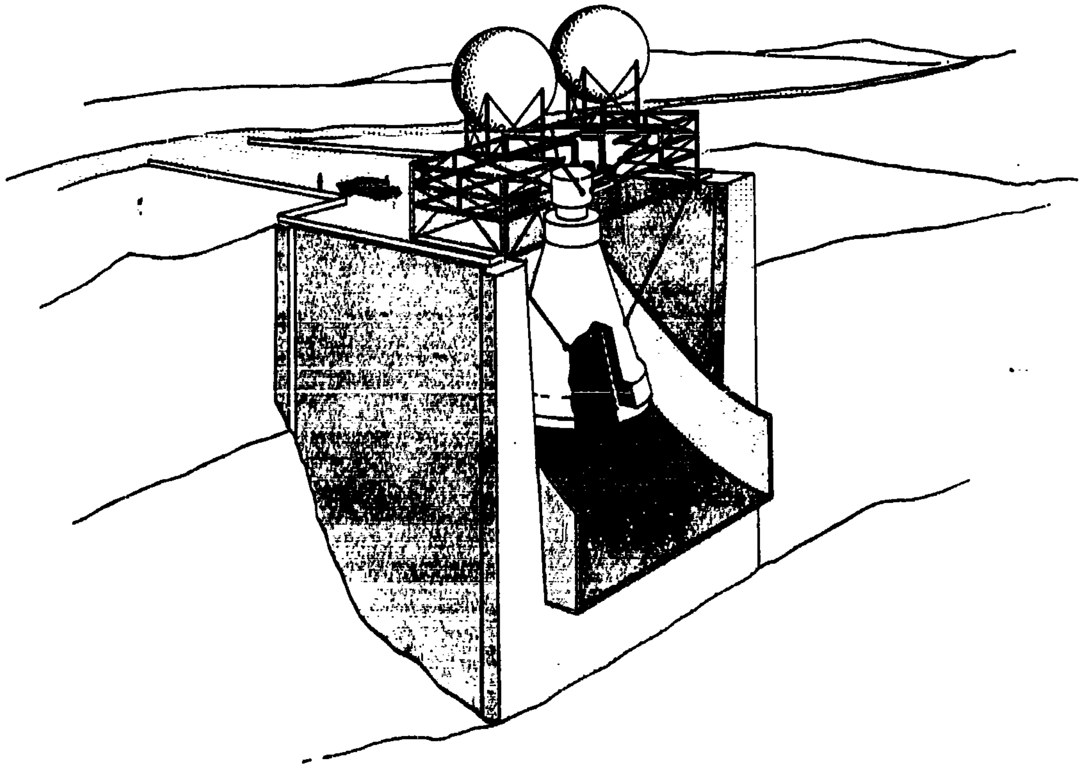

Fig. 27 Artist's conception of a 10,000 MW Rocket-Driven MHD Generator. The generator employs the equivalent of two F-1 engines as the heat source. The estimated installed cost of \$30 million is equivalent to \$3/KW installed. Of this figure, \$20 million or \$2/KW is represented by equipment which is available and in use today in connection with the development of the engines.

SUMMARY

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A 20 Mw MHD generator is presently planned to operate for a period of three minutes in the fall of 1963. There is a high degree of confidence that this MHD generator will perform satisfactorily for a period of several minutes and generate a net power of approximately 20 Mw. The length of operating time has been deliberately limited to minimize R&D costs, and demonstrate technical feasibility.

Experienced engineers in large power system development corporations estimate that the capital investment required for open cycle kerosene and oxygen MHD generators in the 1000 Mw range will be from $3 to $10/kw. The cost of fuel to operate an MHD generator of this size for a few minutes is estimated to be approximately $25,000. The operating life of such an MHD generator is believed to be twenty hours, at which time maintenance and replacement of the wall electrodes would be necessary.

MHD power generation is one of the lowest cost methods of providing multimegawatt pulse power for periods of a few minutes.

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V EXPLOSIVE TRANSDUCERS

EXPLOSIVE (XMHD) GENERATORS FOR ULTRA HIGH POWER PULSES

Arthur T. Biehl

MB Associates

I. INTRODUCTION

Explosive magnetohydrodynamic generators (XMHD) are devices which convert high explosive energy to electrical energy. This is done by performing work on a magnetic field. The energy content of a magnetic field can be increased to large values by compressing it to high field strength. Electricity can then be generated by causing the magnetic field to move through a conductor.

II. HISTORY OF XMHD

The first experimental work on compressing magnetic fields was done by C. M. Fowler at the Los Alamos Scientific Laboratory. His objective was to compress a moderate magnetic field to very high values. A peak field of 14 megagauss was achieved in a cylindrical implosion system. Very large fields were also generated by linearly collapsed copper loops.

The XMHD work at MB Associates has been for specific practical applications. One of these has been a magnetohydrodynamic hypervelocity gun which is being developed for the National Aeronautics and Space Administration. In this device a magnetic field is compressed to high values. The pressure of the magnetic field ($B^2/8\pi$) is used to accelerate a projectile to very high velocities. The required magnetic field is of the order of 2 megagauss, which provides a mechanical pressure of about 2.5 million psi.

Another project at MBA has been the development of a small XMHD generator for the Army Signal Corp Research & Development Laboratory. This generator was specifically designed for driving a flash tube. The project culminated in the successful pulsing of a flash lamp by an XMHD generator.

III. XMHD FOR FLASH LAMPS

Concept of Energy Extraction

The energy of the high explosive is converted by the performance of PdV work on the magnetic field. Because of the skin depth effect, a changing magnetic field will not penetrate a conductor. Conversely, a moving conducting wall will contain a magnetic field because the field within it is rising. The pressure of the magnetic field is given by $H^2/8\pi$. The magnetic field supplies the pressure, the moving wall the dV. The magnetic energy of the system is thus given by

$$W_m = \int PdV = \frac{1}{2} LI^2$$

Theory

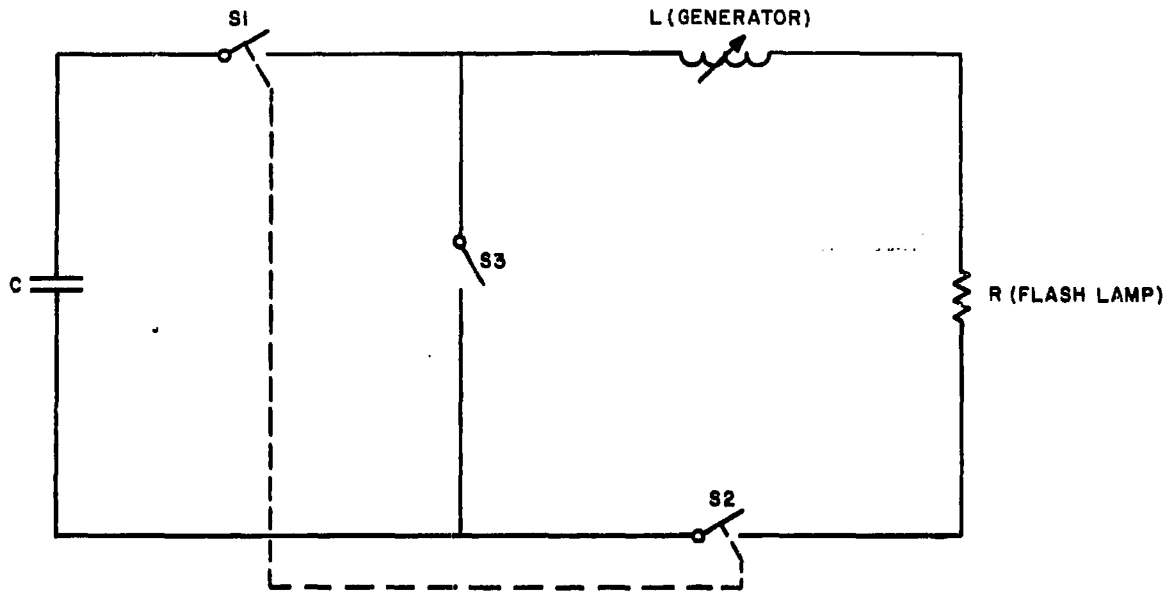
If one is cautious, circuit theory can be applied to the analysis of XMHD generators. Because of the rapidly changing conditions and the large magnetic and electric fields, it is necessary to insure the circuit theory model does not conflict with the basic relations expressed by Maxwell's equations. The dynamics of the system can be expressed in a simplified manner, however, from Kirchoff's Law.

$$\frac{\partial\varphi}{\partial t} + RI = 0 \quad ,$$

where

$$\varphi = \text{magnetic flux} - LI \quad .$$

A system which has been successfully used is described as the "two switch, direct coupled XMHD generator". The simplified circuit diagram is shown below.



The operation of the system is as follows.

1. Condenser C is charged to a voltage which is high enough to break down the flash lamp.

2. Switch S_1 is explosively closed. Simultaneous with this is the closure of switch S_2 which represents break down of the flash lamp.

3. The current in the circuit rises to some peak value which is determined by the circuit time constant. The explosive in the generator is detonated at such a time that switch S_3 is explosively closed when this current and thus the magnetic field is at its peak.

4. The explosive continues on, reducing the inductance of the generator which causes an increase in current and magnetic field. The PdV work thus performed by the explosive appears in a form of electrical energy passing through the flash lamp resistance.

Experiments

Using an XMHD system as just described, energy has been delivered to flash lamps in simple, unoptimized bench experiments. Efficiency in these

experiments has been in the order of 10^{-3}. An efficiency of 2×10^{-2} is theoretically obtainable into a useful load by these small generators. This would require taking care to keep the overall circuit resistance to a minimum.

IV. LARGE XMHD GENERATORS

Requirements

An electrical energy of 10^{10} joules per pulse may be desired. Since the efficiency of these devices increases with increasing generator size, 10% of the total energy content of the high explosive should be realizable as electricity at the load. The pulse width of the electrical output could be varied but would be about 100 microseconds.

Size and Weight

The amount of explosive necessary to provide the 10^{10} joule electrical pulse would be 22 tons. The total mass of the XMHD generator would be about 70 tons. It would be about 8 feet in diameter and 25 feet long.

Hazards

The hazards associated with operating such a device are the blast wave and flying shrapnel. In order to operate close to populated areas, underground containment of the explosive is dictated. A small cavity 125 feet underground should provide complete containment of all effects.

Costs

In production, the cost of XMHD generators capable of delivering 10^{10} joules (electric) would be approximately two dollars per pound. For 70 ton overall weight, this is a cost of about $300,000 per pulse generator.

System Check-Out

Operational check-out of the installed generator system would be accomplished in the same manner as ICBM's. Periodically an operational crew would fire a generator and operate its associated systems.

V. PRESENT STATUS AND RECOMMENDATIONS

The theory of XMHD generators as applied to driving flash lamps and other electrical loads has been well developed at MB Associates. This theory is scalable to any size of generator. Experimental work has confirmed the theory and has successfully produced light output from XMHD-driven flash lamps.

Fundamentally, there are two problem areas associated with XMHD generators at the present time. The most important of these is the necessity for a low overall circuit resistance. Flash lamps or other loads should be especially designed for low resistance and optimum coupling to the generators.

The second problem is the generation of sufficient magnetic pressure for efficient extraction of the PdV work of the explosive. While this is a problem with small generators, the efficiency increases with size of the device. With 10^{10} joule devices, development of adequate magnetic pressures is not expected to be a serious problem.

To expedite early prototype testing of a 10^{10} joule (electric output) XMHD generator, it is recommended that we conduct research and development in the following key areas:

Analysis

1) Determine coil and armature configuration to obtain the desired "PdV work" and efficiency
2) Define the maximum allowable load resistance for reasonable energy conversion efficiencies

3) Determine problems of multiple staging

<u>Engineering</u>

1) Hydrodynamic design

2) Load circuit design (transmission line and flash lamp or other load)

3) Structural design

4) Configuration and design of explosive components and initiators

5) Design of containment volume and access

<u>Testing</u>

1) Test individual components and sub-stage generator assemblies

2) Test scaled-down prototype

3) Test full-size prototype

GENERATION OF ELECTRIC POWER FROM EXPLOSIVES

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MHD Research, Inc.

A. Experimental Study of the Generation of Pulsed Power from Explosives

In experiments presently being conducted at MHD Research, Inc.,(1) peak electrical powers of 1.8 Mw per cubic inch have been obtained by MHD principles from a seeded 10 gram charge of condensed explosives. This power density corresponds to 10^{11} watts per cubic meter of channel volume. Present pulse length is approximately 10 microseconds. Figure 1 is a photograph of the experimental generator. Explosive, in form of shaped charge, surface seeded with cesium picrate, shoots a jet of ionized gas through a 1 inch by 1 inch channel. The channel is placed in the gap of a 22 kilogauss magnet, now shown.

A study has indicated that scaling to larger sizes will be controlled by magnetic Reynolds number limitations. Power densities in the larger sizes will be about 2×10^9 watts per cubic meter. With a generator volume of 5×10^3 cubic meters, the power output of 10^{13} watts for 10^{-3} seconds would deliver a total energy of 10^{10} joules per pulse. It is estimated that the charge of seeded explosive for each pulse would be somewhat in excess of 10 tons. Different explosive geometries may lead to increased power densities, with a corresponding order of magnitude reduction in generator size.

(1) Semi-Annual Technical Report, "Research on the Physics of Continuous and Pulsed Generators", Nonr 3859(00), MHD Research, Inc., February 1963.

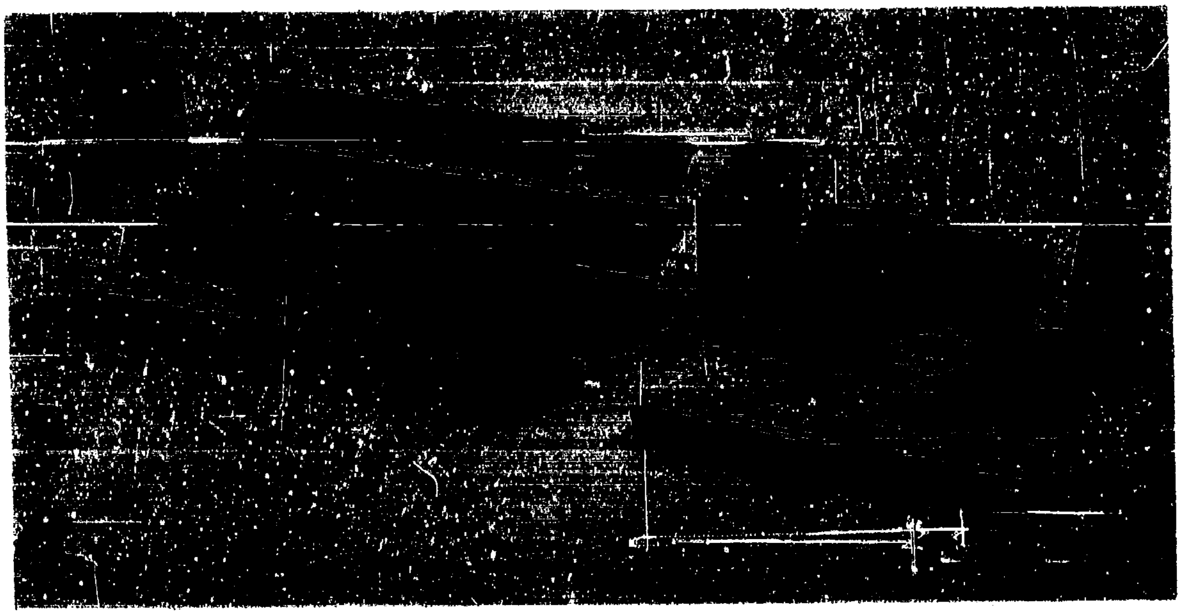

Fig. 1. Experimental XMHD generator

B. Pulsed Power Generation from Underground Nuclear Detonations

Two methods have been considered for extraction of electrical energy from nuclear explosives. The first of these approaches utilizes a factor peculiar to nuclear explosives, namely, the gamma flux. Due to Compton scattering of electrons, the gamma flux sets up a radial distribution of charge which could be collected and dumped into a useful resistive load. Initial calculations indicate a conversion efficiency for this technique of between 10^{-3} to 10^{-4} for time durations of about 1 to 10 sec.

The second approach to electrical power extraction from an underground nuclear detonation is based on an MHD conversion system. In this approach, a nuclear explosion would be used to heat the gases in an underground chamber at constant volume. The heated gases would be seeded with potassium to enhance conductivity as the top temperature decreased. In preliminary analyses a permanent magnet capable of maintaining 5000 gauss over the generator volume was assumed. When the initial total temperature in the chamber is set at 12,000°K, by adjusting yield and total mass of gas (argon), the power density at "quarter blowdown", i.e., when one quarter of the gas has escaped, is still 2×10^9 watts/m^3. Typical values of voltage are 2000 volts at a current density of 50 amperes/cm^2 for a channel with 2 meters electrode separation. For this example, the power flux in the flow through the throat area was taken to be 25 Kw/mm^2, which is an experimentally realizable number as determined from plasma arc jet studies.

<u>Summary</u>: results of preliminary studies have indicated that nuclear explosion-driven, linear MHD generators are feasible and deserve extensive study for potential application at extreme power output levels, $>10^{10}$ watts for times on the order of minutes or less.

SUMMARY

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Institute for Defense Analyses

The technical feasibility of generating megawatts for tens of microseconds with explosive transducers has been demonstrated. Explosive transducers could be developed to provide multi-megawatts for 5 to 10 microseconds for less cost than other technical approaches.

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VI SWITCHING AND CONTROL

PRESENT TECHNOLOGY OF LARGE SWITCHGEAR

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Switching large blocks of power can be divided into two general categories:

Problems associated with energizing a circuit and problems associated with deenergizing a circuit.

These problems become much more difficult when dealing with d-c systems, high rates of current, large magnitudes of current, relatively high voltages and when a multiplicity of operations are required in a short time interval.

I. Problems Associated With Energizing a Circuit.

Possible devices for energizing high capacity d-c circuits may be divided into the following categories:

A. Electro-mechanical switches

B. Silicon controlled rectifiers

C. Mercury arc rectifiers

D. Spark gaps

Under certain circumstances cryogenic devices may fall into this category, but in general do not make ideal high voltage circuit closing devices.

A. Electro-mechanical devices capable of energizing d-c circuits up to 20 kv and capable of initiating the flow of current up to 300,000 amperes have been used in our Short-Circuit Laboratory for the past 10 years.

A. (cont'd)

Experience has shown that they are capable of performing their closing function many thousands of times providing a suitable time interval is available for resetting the closing switch after each operation. This resetting operation must be accomplished with the main power circuit deenergized inasmuch as this switch has no power interrupting ability. In addition, the reset time required is in the order of one second. The time on accuracy of closing of this large switch together with its associated control equipment does not exceed ± 250 micro-seconds to ± 100 micro-seconds. The overall size of this closing switch is approximately 8' high, 2-1/2' wide and 5' deep. The dielectric medium is compressed air at 250 psi.

B. Silicon controlled rectifiers individually are capable of holding of approximately 1000 volts and are capable of withstanding peak currents in the order of 5000 amperes for durations of approximately 20 milliseconds. These devices may be connected in series to increase their hold-off voltage and may be connected in parallel to increase their current handling ability. Suitable voltage distribution devices consisting of resistors and capacitors are effective when cells are connected in series but extreme care must be taken to see that

B. (cont'd)

the cells are not damaged due to improper firing techniques. This is particularly important when the rates of rise of current are rapid. Current handling ability is seriously influenced by the means employed to distribute the current among the multiplicity of cells connected in parallel. Particular care must be taken in examining the effective transient resistance as well as the effect of small inductive loops which may be formed among the multiplicity of current paths used to feed parallel cells. Voltages in the order of 5 to 10 kv can be switched by SCR's up to current levels in the order of 100,000 amperes providing the rate of rise of current is not excessive. While it is possible to switch higher voltage and higher current using SCR's, the care and complexity necessary to accomplish this reliably goes up considerably and therefore an even greater amount of development work would be necessary to accomplish this than that required to switch 5 kv at 100,000 amperes. Inasmuch as solid state devices can be damaged by short duration voltage or current transients considerable care must also be taken to be sure that transients arising in other parts of the

B. (cont'd)

system do not cause misoperation or damage to the solid state equipment. The principal advantage of this type of switching device is that it may be switched frequently and without deterioration providing all elements are operated well within their ratings.

C. <u>Mercury Arc Rectifiers</u>

Operation of mercury arc rectifiers is similar to that of the SCR circuit initiating equipment described above with the exception that mercury arc devices are capable of being worked up to at least 20 kv d-c and in addition have been used for many circuit energizing applications in which the current supplied by large capacitor banks was in the order of a million amperes. These mercury arc devices are capable of energizing the circuit many times without significant deterioration but care must be exercised in being sure that each tube has been completely deionized before voltage is reapplied across it, and in addition suitable cooling means must be provided to dissipate the heat produced in the mercury arc tubes in applications where the duration and the number of applications of current are such that the temperature of the tube may be raised significantly.

D. Spark Gaps

Trigger type spark gaps have been very successfully employed in applications where high voltage, high current or high rates of rise of current have to be handled. With the present state of the art, spark gaps and special mercury arc rectifiers can be used interchangeably in the same kind of applications. The spark gap may show more rapid signs of deterioration than the mercury arc tube in the case where the duration of the current may be in the order of a millisecond or longer and where this current may be reapplied frequently enough so the electrode may heat up significantly.

II. Problems Associated With Deenergizing a Circuit

There are four possible means for deenergizing a circuit based on technology and equipment available today. These are:

a) Abruptly forcing current to zero by current "chopping". "Chopping" is accomplished by arc or plasma starvation in which the amount of energy or amount of charge carriers abruptly decreases to a value that they will no longer support the amount of current previously carried. Current "chopping" always produces extremely high overvoltage unless suitable surge suppressing

a) (cont'd)

equipment is provided. In addition, current "chopping" can usually be accomplished only at current values less than a few hundred amperes.

b) Current can be interrupted by controlling a plasma or arc in such a manner that the arc or plasma voltage is significantly higher than the system open circuit voltage and so that it remains higher for a period sufficiently long to absorb the energy stored in the inductive components of the power system. For high current circuits this means a significant amount of the energy may be dissipated in the interrupting device with the attendant deterioration of the interrupting device itself and a considerable loss of system energy. In general, high current arc voltages in excess of a few kv are difficult to obtain in a single arc or plasma, but it is possible to obtain the high arc voltage if a multiplicity of arcs are connected in series.

c) In the case of d-c circuits where the system does not provide a natural current zero, it is possible to force a current zero by connecting a capacitor across the switching device providing that device is in a position to interrupt the current when the attendant high frequency

c) (cont'd)

current zero is reached. This means that the interrupting device must be capable of withstanding the high attendant rate of rise of recovery voltage immediately following the very rapid rate of decrease of the current which was attained by means of the switched capacitor. By careful examination of the overall system including the distributed inductance, resistance and capacitance elements of the system it is possible to control the rate of change of current, the rate of rise of recovery voltage and the peak magnitude of the recovery voltage by suitably choosing a capacitor with the proper characteristics. This capacitor switching scheme could possibly be used in conjunction with electro-mechanical arc interrupting devices in which the current is carried in the arc plasma, or in suitable arranged solid state devices such as SCR's or possibly in mercury arc devices providing the deionizing characteristics can be satisfied.

d) Cryogenic switching devices could also be employed providing the energy dissipated during the switching operation under the high current, high voltage conditions would not damage the device and also providing suitable cooling could be obtained rapidly enough if a multiplicity of operations of a single device were

d) (cont'd)

required. The accuracy of switching being thermally controlled or possibly magnetically controlled may present some rather formidable problems if reasonably accurate control is required.

III Equipment Which May be Utilized For Deenergizing a High Capacity Circuit

a) Electro-mechanical devices may be considered providing the total energy dissipated and the interval between operations is commensurate with that of the application requirements. 5000 volts d-c can be interrupted at current levels in the order of 100,000 amperes but there is no device readily available today with these ratings, nor are there any devices available to handle this kind of capacity where a multiplicity of operations are required in a short interval of time, but if necessary we believe that with an extensive development program a device of this capability could be produced. By connecting a multiplicity of these devices together and feeding them from individual power supplies, it is possible that capacities considerably in excess of this could be obtained. Voltages in excess of 5000 volts can be interrupted by electro-mechanical devices when used in combination with a switched capacitor which would

a) (cont'd)

force a current zero. This would permit the use of an interrupting device in which the arc voltage or plasma voltage is considerably less than the open circuit system voltage, the principal requirements of the interrupting device in this case being such that it can withstand the transient recovery voltage immediately after the forced current zero.

b) Series-parallel combination silicon controlled rectifiers with appropriate current distribution and voltage distribution can also be employed as a current interrupting element when used in combination with a suitable switched capacitor providing the thermal capability and transient voltage capability as well as the turnoff characteristics of each of the individual solid-state components are not exceeded.

c) Mercury arc rectifiers may be substituted for silicon controlled rectifiers providing the deionizing characteristics of the mercury arc tubes together with their energy handling ability and their degassing properties can be met. A circuit similar to that employed with the silicon controlled rectifier would be necessary if mercury arc tubes are used as the

c) (cont'd)

interrupting element. In this case the requirements of the Kingdon factor would have to be met on a reliable basis when the tubes are subjected to a multiplicity of interruptions within a short time interval.

In order to arrive at the most effective, practical and reliable equipment necessary to initiate and to stop the flow of large blocks of d-c power, it will be necessary to carefully examine the transient characteristics of the overall system including that of the load. In addition, the distributed as well as the lumped inductance, resistance and capacitance of the system must be studied thoroughly in order to obtain a good reliable means for initiating and stopping the flow of the d-c power. In any event the magnitudes of energy discussed are so large that we know of no devices that have been developed to date which are directly suitable for this application. Therefore considerable development work would be required to do the job, but we feel that if the system and load conditions are known suitable switching devices can be provided within the framework outlined above.

SWITCHING INDUCTIVE-ENERGY-STORAGE APPARATUS

Harold C. Early

University of Michigan

When the current in an energy-storage coil has reached its peak value, a switch is opened to transfer the current into the load. The requirements for this switch are substantially different from those for existing types of commercial circuit breakers. First, the operation must be much faster. If the stored energy is to be delivered to the load over an interval of several milliseconds, then the switching operation should, if possible, take place in a millisecond or less. Second, since the circuit does not open at a current zero, as in an a-c breaker, there will, in general, be substantial voltage across the arc that is being interrupted.

These switching requirements also depend on whether the resistance or the inductance of the load is the dominant factor. If the load is purely resistive, then the switch should open the circuit in the minimum possible time, and the energy dissipated in the switch decreases as the switch opening time decreases. If the load is purely inductive, then the energy to be dissipated is approximately independent of the switch opening time, and the energy dissipated is equal to the total stored energy, multiplied by the ratio $\frac{\text{load inductance}}{\text{coil inductance}}$. The minimum switching time is then limited by the rate at which energy can be dissipated by the switch as well as the maximum voltage that the circuit can withstand.

For switching an energy-storage coil of 10^9 to 10^{11} joules, the switch would need to dissipate energy of the order of perhaps 10^8 joules in a time interval of the order of a millisecond. With conventional, mechanical switches designed for carrying heavy currents, it is difficult to physically break a metallic circuit and achieve any significant contact separation in a time interval of the order of a millisecond. Also, dissipating energy of the order of 10^8 joules in a millisecond by air-blast or magnetically driven arc breakers would involve a very large volume of gas and very bulky apparatus. The large bulk of the apparatus would increase the inductance and hence increase the energy to be dissipated.

One solution to the fast switching problem is to utilize the high voltage gradients, high energy densities, and high energy absorption properties of plasmas at extremely high pressures. As an example of the amount of energy expended in forming a very-high-pressure plasma, some numerical figures are pertinent. A study of an underwater spark at the University of Michigan by Prof. E. A. Martin (Ref. 1) showed a good agreement between experimentally measured and calculated plasma properties. The following conditions existed at 1.9 microseconds after initiation:

Plasma pressure--10,000 atmospheres

Plasma temperature--30,000 °K

Diameter of spark channel--2.5 millimeters

Current--85,000 amps

Plasma energy density--3 x 10^9 joules/meter^3

Voltage gradient in channel--5.5 kv/cm

The plasma was 100% dissociated and 30% ionized. At still higher temperatures, the additional energy expended in ionization causes large increases in the energy absorption.

This high energy absorption at very high pressures has been found to be very effective for switching inductive-energy-storage apparatus (Refs. 2, 3), using the arrangement shown in Fig. 1. A fast acting mechanical switch* is shunted by a fuse and a load. The fuse operates at gas pressures in the range of 20,000 to 40,000 psi. It consists of a fiberglass tube with a fuse wire down the center. The space between the copper fuse wire and the wall of the tube is filled with oil to increase the plasma confinement and pressure. In operation, the mechanical switch opens and the current transfers to the fuse wire which carries the current for several milliseconds, allowing time for dielectric recovery in

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*A very inexpensive low-inductance switch for approximately 100,000 amperes was made by using a heavy, three-bladed knife switch obtained from abandoned street-car facilities. This switch is used in conjunction with an air cylinder and latching mechanism. The force due to the air cylinder, as well as the magnetic force, tends to open the switch but is restrained by a latch pin that is released by firing a squib. The velocity of contact separation is approximately 2 cm per millisecond.

the mechanical switch, before the wire explodes. As the wire explodes, the voltage drop across a foot-long fuse will rise to 50 kv in about 0.2 millisecond. Five fuses of this type have been used in parallel (Ref. 3) to switch 125,000 amperes of current.

When this type of fuse "blows", the initial high voltage is due to pressure confinement of the plasma. In order to avoid exceeding the mechanical strength of the confining walls, the fuse is vented at the ends. The high velocity and turbulence of the gas and oil venting through the ends are important factors in maintaining the high voltage across the fuse over a longer time interval.

This fuse-switching method might be scaled up to handle millions of amperes. However, the use of dozens or hundreds of parallel fuses appears cumbersome, and there might be objectionable time jitter in the operation of the mechanical switch. The amount of current, energy, and pressure that could be handled by any one fuse wire or ribbon would be limited by the mechanical strength of the confining dielectric material. A large fuse might be built using a dielectric-lined, naval-cannon barrel, which would withstand confining pressures of the order of 100,000 psi, and the required amount of energy might be dissipated without venting. Such a fuse might not become a complete open circuit after blowing, but would still transfer the major part of the current into the load.

An alternative confining method might use only the inertia of the confining medium as in an underwater spark. However, the extremely high confining pressure in the underwater spark lasts for only a few microseconds because it is rapidly relieved by the motion and compression of the water. The use of a chemical explosive to compress the liquid surrounding the fuse wire just as the fuse blows is a possibility, but, again, the problem of maintaining the pressures for millisecond time intervals requires large amounts of explosive. Ref. 4 gives data regarding underwater explosions applicable to this problem.

A fuse suitable for switching 10^9 to 10^{10} joules of stored energy would be a one-shot, completely expendable device. Present information suggests that the best design might be as follows:

1. A chemical explosion would create a strong shock wave in water or other liquid surrounding a metallic conductor.
2. The high-velocity shock wave would break the metallic ribbon conductor in a number of locations, and multiple arcs would be initiated.
3. The high pressure associated with the shock wave, as well as the self-generated pressure of the under-liquid arc, would result in a high-density plasma having high energy absorption and a high voltage gradient.

4. The high flow velocity of the liquid surrounding the multiple arcs would cause them to impinge against obstacles, thus lengthening, flattening, and contorting the arc columns and creating turbulence. Droplets of the liquid might also be dispersed into the plasma to further increase the rate of heat loss.

Current Interruption Due to "Ion Starvation"

An evaluation of various methods of quickly interrupting a very high current discharge should consider the phenomena associated with "surging" of ignitron rectifier tubes. Ignitron rectifiers, carrying heavy currents, will at times suddenly "cut off" and cease conduction and develop inductive voltages in the circuit large enough to flash over the external insulation. There is divergence of opinion as to the cause of surging, but it is related to the fact that a high voltage gradient in the ignitron causes heating of the conducting plasma which decreases the ion concentration. With insufficient ion concentration, the voltage drop and the ion temperature continue to increase, and the ion concentration continues to decrease. The current then suddenly drops to a much lower value.

The phenomena causing surging due to low ion density in a mercury-vapor tube could perhaps be utilized in designing a device to as a circuit interruptor. Such a device would

not be expected to dissipate a large amount of switching energy, but it might be used to suddenly transfer the current into a shunting Thyrite-type, non-linear resistance which would dissipate the energy required to transfer the current into the load.

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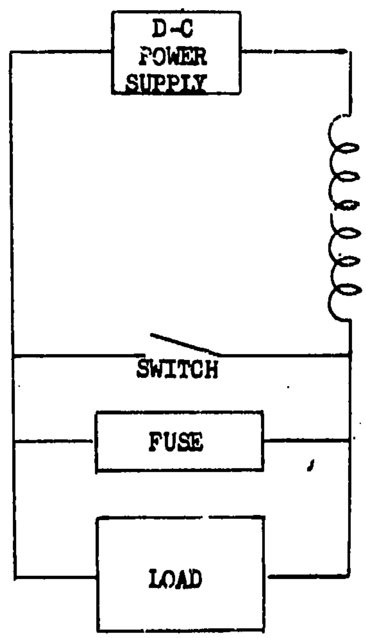

Fig. 1. Basic switching system

SUMMARY

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Deenergizing large d-c inductive-energy-storage coils is today's principle switchgear problem associated with high pulse power systems. Five kv d-c at 10^9 amperes can be interrupted with switchgear which can be built today, but is not readily available. Since this conference the development of vacuum switches which can interrupt 15,000 amperes at 40,000 volts, and in the near future 100,000 amperes at 37,000 volts has been reported. These switches can open in a few milliseconds, reclose in 300 milliseconds, and have a life of 200 cycles.

H. C. Early suggests that 10^9 joule expendable fuses could be built which utilize a chemical explosive to create a shock wave to break a metallic fuse ribbon in several places to create multiple arcs. These multiple arcs in an oil-filled insulated tube would provide a high density plasma with large energy absorption and voltage gradient characteristics. The high pressure plasma in the tube would generate high velocities to quench the multiple arcs.

High current d-c switching is a relatively neglected technical field, and the achievement of very high peak pulse powers in small fractions of a second is limited by switchgear current interrupting capacity. The development of higher current and voltage capacities in fuses could appreciably reduce the total cost of high pulse power systems.

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VII GENERAL SUMMARY

GENERAL SUMMARY

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The battery-inductor system will require a smaller capital investment than other available energy storage systems to provide energy in the range of 10^8 joules for hypersonic wind tunnel testing.

MHD-inductor pulse power systems could be built in the near future for a capital investment nearly comparable to the battery-inductor system. When maintenance and battery replacement costs are considered, the total cost of fabrication and operation of the MHD-inductor pulse power system will be less than that of the battery-inductor system.

When developed in the size required, the explosive transducer may be the least expensive method of generating megajoules.

Today's switching technology limits the quick and efficient disconnecting of large inductors from loads.

Pulse power systems are <u>not</u> the pacing element either technically or economically in the development of defense weapons. Any one of several pulse power systems could be built and used satisfactorily depending upon the amount of development time available. Pulse power systems represent approximately 15% to 25% of the total weapon system cost.